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OPTICAL SCANNING USING ELECTRICALLY-MODULATED MEMBRANE MIRRORS

SEMI-ANNUAL TECHNICAL REPORT NO. 2
FINAL REPORT
January 1962 - December 1962

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NOTES:

Throughout this report Semi-Annual Technical Report No. 1 under the subject contract will be referred to as Report No. 1.

Copies of those figures in Report No. 1 which are referred to in this report have been included at the end of this report for convenience. As the last figure in Report No. 1 is Figure 73 the first figure in this report is Figure 74.

For those wishing to study this development closely it is recommended that a copy of Report No. 1 be available for reference.

1. BRIEF REVIEW OF THE PROJECT INCLUDING THE BACKGROUND WORK

It is well known to both fabricators and users of optical components that rigid lenses and mirrors present several difficult problems which become acute when large apertures, high-accuracies, and low F/numbers are required. When optical components are needed for space applications their weight and thermal distortion may impose additional engineering problems. Many space applications also necessitate that optical components together with other associated components be expendable after relatively brief use. In the case of large aperture components of high precision the dollar loss can be extremely high. Realization of the above problems leads to the consideration of what other type of optical component construction might be utilized.

One radically different type of construction which has been conceived is the use of a thin membrane curved to form an optical surface. In the case of a lens a suitable liquid or gas would have to be held between two membranes to provide optical refraction. This type of construction would be extremely difficult to use, particularly for space applications, due to the inertia of the fluid fill, the possibility of fluid leaks and the widely-changing thermal conditions in space. However, reflective type membrane optical components can be designed which are considerably more practical. An objective mirror can be produced by electrostatic attraction of a normally-flat, reflective and conductively-coated base membrane. To date substantially all effort has been devoted to this last type of optical component.

Electrically-deflected membrane mirrors offer the advantages of low optical figure distortion due to temperature changes, low weight, low production cost (after fabrication techniques are developed), electrical figuring of the optical surface and electrical focusing. In addition they offer the possibility of optical axis deviation by electrical means. This last feature provides the advantage of almost inertialess operation and will be useful for scanning and tracking functions.

While the potentials needed for membrane deflection are in the order of kilovolts the power required for static deflection is only that dissipated by electrical leakage and that required by voltage regulation circuitry. These can be held quite low by appropriate design. The high vacuum of space should provide a favorable environment for the maintenance of high electrical insulation and uniform mechanical properties of the membrane.

One ultimate goal of the development of membrane mirrors is to make available expendable precision mirrors of very large aperture at substantially lower cost and weight than rigid mirrors. The usefulness of such mirrors for space reconnaissance, scanning and tracking purposes and also for astronomical observation is obvious. Due to the radically-different construction and low mass of membrane mirrors their optical figure distortion due to thermal variations should be considerably less than that of comparable rigid mirrors. This offers the possibility of a closer approach to diffraction-limited operation, particularly when large aperture mirrors are considered.

Under NASA Contract NASW-100 the first experimental results using membrane type mirrors were obtained and reported by Irco Corporation during 1960 and 1961. This work is presented in Section 2. of Report No. 1. The final goal under the above contract was to produce a 7 inch diameter, F/5 parabolic mirror accurate to 1/20 wavelength. Due to unanticipated limitations of the degree of vacuum attainable with the vacuum apparatus then available for deposition of conducting and reflective metal an accuracy of only about 1/15 wavelength was achieved over the inner 70% of the aperture of a 4 inch diameter, F/8 mirror. Again, due to vacuum apparatus limitations the accuracy obtained for a 7 inch diameter, F/6 mirror was only about 1/2 wavelength over the inner 75% of the aperture. It was believed, however, that with an adequate vacuum system much larger parabolic mirrors could be produced having higher accuracy over their full aperture. Since the quality of flat mirrors is not closely dependent upon angular uniformity and precise radial distribution of vacuum deposited metal 7 inch diameter optical flatswere routinely made to accuracies of 1/20 wavelength as a necessary step during experimental attempts to produce a 7 inch diameter parabolic mirror of the same accuracy.

During the above work a few tests were run using 7 inch diameter membranes deflected to F/1.0. While these deflections were not sustained for periods longer than 12 hours it has been tentatively assumed that focal ratios of F/3 to F/2 can be realized over substantially unlimited periods.

During December, 1960 it was proposed to ARPA that the flexibility of the membrane type mirror might also be utilized to produce optical scanning by subjecting the membrane to periodic electric fields superimposed upon the static electric field used to produce the normal optical curvature. If successful, such a system would have the advantage of being very nearly inertialess since the membrane weight is negligible (in the order of 1/10 gram for an 18 inch diameter mirror.)

The object and essence of the present development has been to obtain significant deviations of the cptical axis of membrane type objective mirrors while at the same time maintaining useful but not necessarily diffraction-limited resolution of "point" targets. Specifically, it was desired to utilize an 18 inch diameter electrically-deflected membrane to achieve one milliradian resolution of the image of a distant point target while its image was moved $\pm$ 0.5° by electrical movement of the membrane mirror. This resolution should be achievable at F/3 or lower and when the target is at any point between 0° and 2° from the reference axis. If such optical axis deflection can be accomplished in one plane, as it has been in this development, the scanning problem will be solved since axis deviations in two mutually-perpendicular planes can be combined to produce a circular or any other desired scan pattern.

In this development it was necessary to develop the apparatus necessary to produce large membrane "stock" sizes of high uniformity together with apparatus for applying this membrane material to 18 inch diameter support rings with extreme precision and for applying a reflective and electrically conductive coating by evaporation during rotation of the membrane mirror about its optical axis. During the course of this development it was necessary to abandon the originally-envisioned electrode and membrane design and to devise an entirely new one.

In this project it should be noted that insofar as optical performance was concerned it was necessary to attempt to duplicate the precision attainable with rigid optical components of high quality. Since the techniques for fabricating accurate rigid optical components have evolved over at least the last century it should be realized that this development entailed many new and difficult problems which have never before been encountered and which had to be solved within a relatively short time. The mirror assembly itself and much of the apparatus used for its construction had to be of a precision comparable with that which would be needed in apparatus intended for end use. It was therefore necessary to devote an unusually large portion of the total effort to the development and precision construction of the experimental scanning mirror assembly and essential supporting apparatus.

With the final experimental design deflections of 0.5° on each side of the reference axis were obtained at F/3 for 11 inch apertures with point target resolution of about one milliradian, except for slight irregularities in the image disc estimated to contain about 25 to 30% of the total energy of the target image.

Report No. 1 covers the following subjects in detail:

a. Background work performed for NASA in connection with high resolution objective mirrors. This work was limited to

4 inch and 7 inch diameter mirrors.

b. Preliminary work performed under this contract in connection with basic membrane problems, optical testing methods, electrical figuring of membrane mirrors, modulation of focal length by a superimposed AC voltage, membrane vibrational modes, gravity sag and consideration and analysis of various membrane strain components.

c. Description of the first experimental mirror assembly having means for electrical figuring and for electrical deviation of the optical axis. This mirror assembly was not completed at the time Report No. 1 was prepared.

d. Description of the various items of supporting apparatus needed to fabricate and apply membranes to the above experimental membrane mirror assembly. This apparatus was only partially completed at the time Report No. 1 was prepared.

2. APPARATUS DEVELOPMENT AND EXPERIMENTAL RESULTS

a. Membrane Casting

The casting tank shown in Figures 68 and 69 was modified and improved as described below:

(1) Since the tank was constructed of sheet aluminum a layer of hard plastic (REN Plastics Inc., Lansing, Michigan, Type RP-3270-A resin and hardener) 1/32 to 1/16 inch thick was applied by brush to its inner walls to prevent corrosion by the casting water.

(2) Since low velocity convection currents were frequently noted on the water surface during initial membrane casting trials a piece of 4 ft. x 4 ft. polystyrene grid stock was laid symmetrically on each side of the deep vertical tank section as may be seen in Figures 74, 75, 76 and 77. The grid walls were 0.085 inch thick and formed 1/2 inch walled squares approximately 1/2 inch high. This plastic material is primarily used as a decorative fluorescent light diffuser. It was supported in the shallow side tank so that it was about 1/8 inch below the water surface. Since its cellular structure reduced movement of the water surface to a visually imperceptible magnitude it was permanently installed in the casting tank and used in all subsequent casting operations.

(3) The front and rear sheet plastic covers visible in Figures 74 and 75 were added to prevent dust from falling upon the casting water surface. Note the image of the front cover reflected by the membrane.

FIGURE 74

FIGURE 75

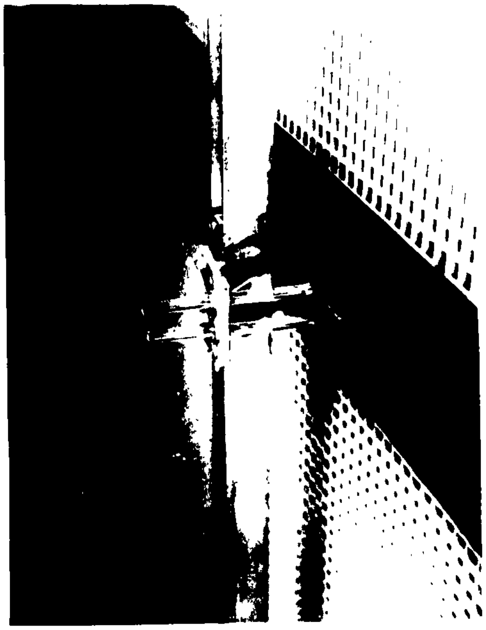


FIGURE 76

FIGURE 77

(4) During initial membrane casting trials the casting solution was hand-dropped at the center of the tank but the resulting membranes did not have sufficient length to cover the removal card with an excess of material sufficient to insure membrane thickness and tension uniformity down to the bottom of the 35 inch diameter hole in the removal card. Further experiments were made with simultaneous dropping of equal amounts of casting solution at two points equidistant from the deep tank on the long axis of the tank. These experiments showed that the long-axis dimension of the cast membranes could be increased in the order of 41 inches, an entirely adequate amount. However, membranes cast in this manner invariably showed an irregular interface along the length of the deep tank.

Since the above-indicated irregular interface would cause undesired uniformity variations at the top of the membrane an automatic dropping system was devised as shown in Figures 76 and 77. This system consisted of an aluminum beam with two small motor-driven sleds arranged to start at the center of the beam (over the deep tank) and move outward along the long axis of the tank toward each end. Each sled contained a vertical pipette having a short piece of latex rubber tubing over its bottom opening. The casting solution could be held within the pipettes by bending the rubber tubes over the screw at the center of the beam as shown in Figure 76. At the instant the sleds were moved by the motor in opposite directions the rubber tubes flipped off the screw and opened thereby allowing the casting solution to flow upon the water surface as shown in Figure 77 at the rate of about 0.5 milliliters/second over a distance of

28 to 46 inches on each side of the tank center. Splashing was avoided by adjustment of each rubber tube to provide about 1/4 inch clearance between the water surface and its open end after release. Since the speeds of the sleds were identical in opposite directions due to a common nylon drive cable and the pipettes and rubber tubes were identical this dynamic dropping system produced extremely uniform results. It was noted that membranes cast in this manner were consistently of high uniformity and showed no interface at the center while the overall length of the cast membranes was increased by 52 inches relative to dropping from one point at the center of the tank.

b. <u>Membrane Casting Solution</u>

In an effort to simplify the casting solution formula the solution designated as Number 3 on Page 62 of Report No. 1 was used in initial membrane casting experiments. When deflected to F/3 these membranes invariably stretched a sufficient amount to become completely limp so that in the undeflected condition they appeared like a loose leather curtain. Surprisingly, however, such membranes showed highly uniform and repeatable optical figures when deflected electrically and only a slight further stretch after 10 - 15 minutes. To obtain membranes which remained stiff the original NASA formula designated as Number 1 was used without the addition of nitro-benzene. Due to the inclusion of glyptal lacquer in this solution formula limpness was reduced to an extremely low value. This formula was used for casting all subsequent membranes and is as follows:

24 ml pentyl acetate (formerly designated as n-amyl acetate)

16 ml flexible collodion

8 ml non-flexible collodion

5 drops glyptal lacquer

The precise specifications for these materials are given on Page 61 of Report No. 1. Pentyl acetate, Catalog Number 2360, Distillation Products Industries Division, Eastman Kodak Company, Rochester, New York was substituted for the n-amyl acetate previously used. The above company stated that this chemically-equivalent material is no longer designated n-amyl acetate in their catalog.

c. Membrane Removal From The Water Surface

(1) A motor drive was provided to lift the removal card shown in Figure 67 from the tank as shown in Figures 74 and 75. This drive utilized a 7 KVA General Radio Type 50B variac to energize a variable speed motor (The Brockmeyer Company, Dayton, Ohio, Type RM, 60 cycle, single phase, 115-230 volt, 1/2 H.P., 550-2500 RPM) which drove a 5/8 inch diameter shaft which served as a windlass by means of a 19:1 pulley and belt reduction. The windlass utilized a single turn of 7/64 inch Nylon rope at each end to raise or lower the removal card within the deep vertical tank section. These parts may be seen at the top of Figures 74 and 75. The differential length of these ropes could be adjusted by means of screw eyes threaded in the metal removal card so that the top edge of the card could be made to emerge from the water surface parallel with the water surface. The 80 pound weight of the aluminum removal card was not counter-

balanced. However, due to pulley, belt and motor friction the card remained at any elevation when the motor was not energized. This motor drive system permitted very uniform movement of the removal card out of the deep tank at rates from 0.6 to 6.0 inches/second by appropriate adjustment of the variac. Due to the unbalanced weight of the removal card the card could be lowered into the deep tank as slow as 0.02 inch/second by adjustment of the variac to provide the small amount of power needed to overcome friction. The rate finally used for removal of cast membranes was 1.5 inches/second while rates as low as 0.15 inch/second were found to be necessary when one or more previously cast membranes were lowered on the removal card into the deep vertical tank prior to casting and adding an additional membrane as described in Report No. 1. It was found that if the lowering rate were significantly higher the previously-cast membrane would occasionally peel off.

d. Membrane Handling

Since the 80 pound removal card was too heavy to be handled manually a crane was provided as already described on Pages 102 and 103 of Report No. 1. This crane was constructed using standard sliding door hardware which can be seen at the top of Figures 74 and 75.

e. Membrane Application Apparatus

This apparatus was completed functionally as described on Pages 103, 104 and 105 of Report No. 1. In the final apparatus support beam 1 shown on Schematic Diagram Figure 71 was actually constructed as a bridge frame as shown in Figure 70 in order to insure adequate rigidity. The application apparatus proved generally satisfactory but required very careful adjustment of the parallelism between the membrane and the pyrex membrane support ring at the instant of contact. Such adjustments required the expenditure of several membranes before adequate precision was achieved. It was found necessary to maintain separate adjustment data for each membrane support ring since these rings varied in height by as much as 0.2 inch. In future work considerable time might be saved by fabricating all such rings to the same height to within $\pm$ 0.001 inch.

It was found that the adhesive mixture used (fresh homogenized milk diluted by four parts cold water) dried too rapidly in the low humidity laboratory atmosphere that prevailed during the winter season. Therefore the adhesive material formula was changed to undiluted homogenized milk. This formula proved satisfactory and remained wet sufficiently long to permit the support ring to be sprayed and the removal card and membrane to be laid in place and for the membrane to be brought into contact with the membrane support ring surface by the motor drive before drying.

The adhesive mixture was sprayed upon the support rings using a General Airbrush Manufacturing Company Type V-2 air brush while the support ring was rotated at one revolution/second. The spray was directed from outside the ring toward the center to avoid placing the adhesive material upon the inside surface of the ring. A minimum of adhesive was used.

The motor drive lowered the membrane toward the membrane support ring at the rate of 0.005 inch/second.

f. Membrane Baking

Prior to evaporation of conductive and reflective metal upon the membrane after attachment to its support ring it was baked at 100°C for one hour in air to remove residual water and solvent materials.

g. Rotary Evaporation System For Application Of Metal Coatings To The Membranes

The rotary vacuum system shown in Figure 78 included a metal bell-jar 30 inches high x 25 inches diameter. A vacuum of 10^{-5} - 10^{-6} mm of Hg could be obtained without liquid nitrogen cooling. Since the collodion membranes generated a negligible amount of organic molecular contamination nitrogen cooling was not used. The above-indicated degree of vacuum proved adequate for evaporation of gold upon experimental membranes and was routinely used throughout the development. Since gold provided adequate electrical conductivity and reflectivity for test purposes no other metals were used since the essence of this development was to achieve the performance given in Paragraph 9 of Section 1 of this report. The perfection of other reflective coatings is believed to be a relatively minor development problem to be solved when a prototype system is developed for a specific application. Figure 78 shows the support used to rotate the membrane on its pyrex support ring above the hot gold sources during vacuum evaporation.

Various radial distributions of gold were originally tried to facilitate optical figuring, that is, to reduce the potential differences required between adjacent optical figuring rings. However, since the presence of the internal deflection electrode reduced the number of field lines acting upon that

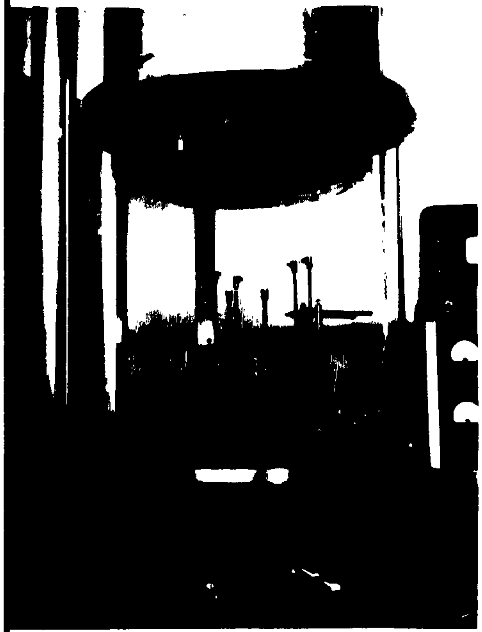


FIGURE 78

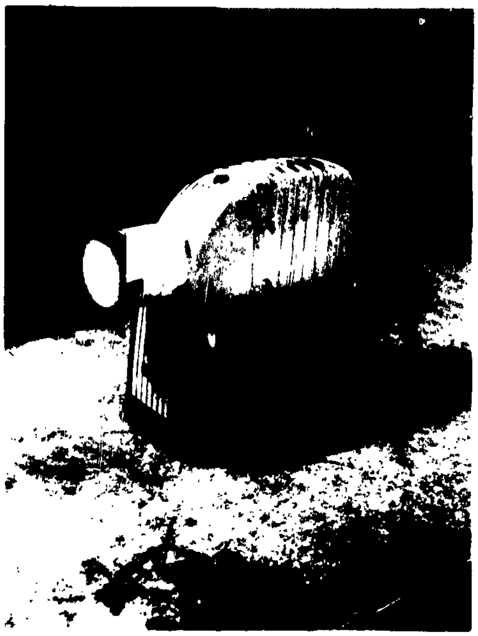


FIGURE 79

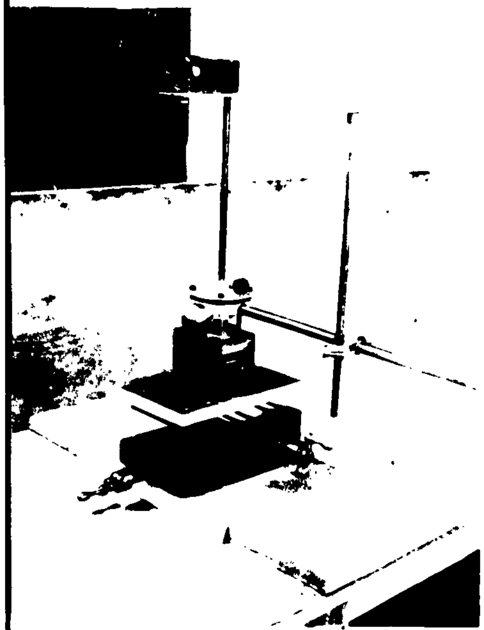


FIGURE 80

FIGURE 81

portion of the membrane adjacent to the inside edge of the aperture formed by the deflection electrodes the typical flat-bottomed figure of the basic membrane discussed on Pages 93 and 95 of Report No. 1 tended to be over-compensated. It was found with the deflection electrodes used in the final design described below in Section 2.1. that a slightly non-uniform radial distribution of the metal coating on the membrane required maximum potential deviations from average of not over 500 volts between adjacent figuring zones. This radial distribution resulted from the use of two gold sources for evaporation. One source was located on the rotational axis 8.5 inches from the membrane and the other 3.0 inches from the rotational axis 7.0 inches from the membrane. Therefore, in the final mirrors produced for deflection experiments the above radial metal distribution was held relatively constant for the purpose of simplicity and all further optical figuring was accomplished electrically.

h. Optical Test Apparatus

Membrane mirrors were tested as described on Pages 70, 71, 72 and Figures 61A and 61B of Report No. 1. Figures 79, 80, 81, 82, and 83 show, respectively, the Kodaslide Master 1000 watt projector used for illumination of Ronchi source grids or "point" target apertures, two views of the interception grid and projection screen, two views of the screen and magnifier assembly for observation of "point" target images, and the auxiliary light source and grid assembly occasionally used to observe mirror errors relative to a true sphere, as described on Page 66 of Report No. 1. In Figures 81 and 83 it may be noted that transparencies of grid No. 6 (Page 72, Report No. 1) were used for target image measurements.

FIGURE 82

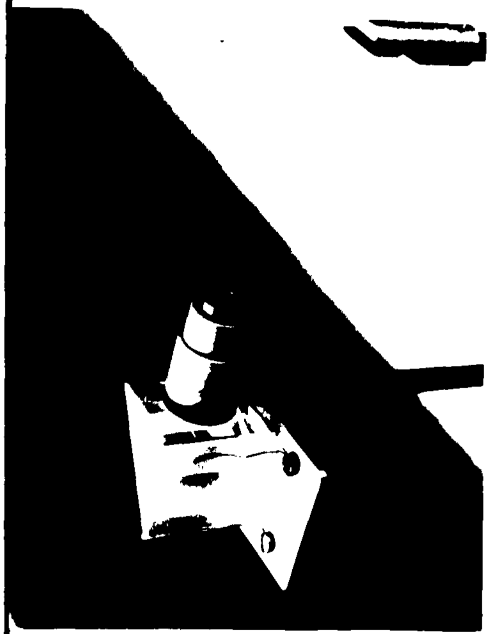


FIGURE 83

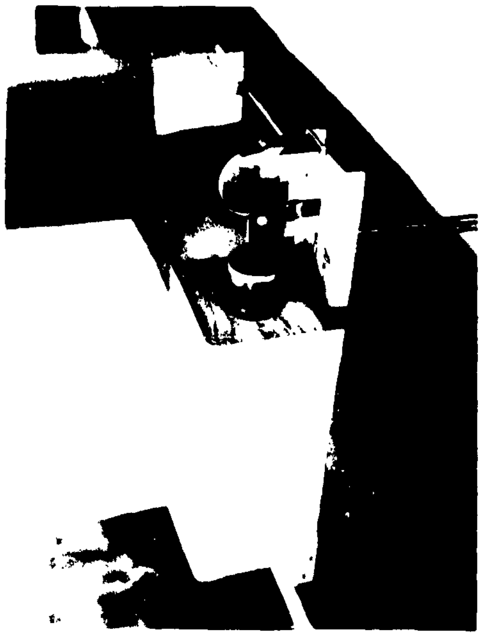


FIGURE 84

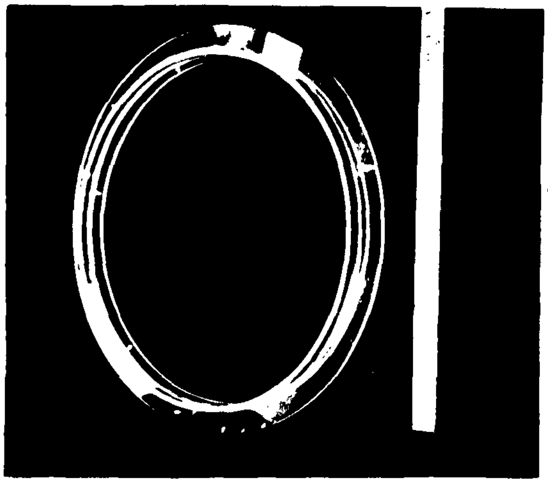


FIGURE 85

i. Results Using The First Experimental Membrane Mirror Assembly

The details of this apparatus are shown in Figures 72 and 73 of Report No. 1. Figures 85, 86, 87 and 88 show, respectively, the membrane support ring, the crossed-wire, grid-type deflection electrode assembly, front and side views of the complete assembly shown in Figure 72. The membrane support rings were constructed of pyrex glass. The flat stiffening ring which can be seen in Figure 85 was 5/16 inch thick and was cemented to a short tube section cut from an 18 inch diameter pyrex vacuum bell-jar using epoxy cement, Anchor Alloys, Inc., Brooklyn, New York, No. 306 "Schurbond" epoxy glue and hardener. These short tube sections averaged 5/16 inch in thickness and their widths ranged from 1.3 to 1.5 inches and were held uniform in thickness within ± 0.005 inch by grinding. The surface to which the membrane was attached was ultra-fine diamond-ground flat to within 5×10^{-6} inch or better. Care was taken to minimize chips around the inside edge of the precision flat surface and to limit their average size to about 0.005 to 0.010 inch below the flat surface. The deflection electrode assembly shown in Figure 86 was constructed of 5/8 inch thick plexiglas and the electrode wires were 0.010 inch diameter. Each wire was spring-loaded at one end to prevent electrical shorting between wires if any became loose. A similar plexiglas ring without electrode wires was used as a spacer. The main or curvature-producing electrode was constructed of selected ultra-flat 5/16 inch thick plate glass. The actual deflection electrode surface consisted of evaporated

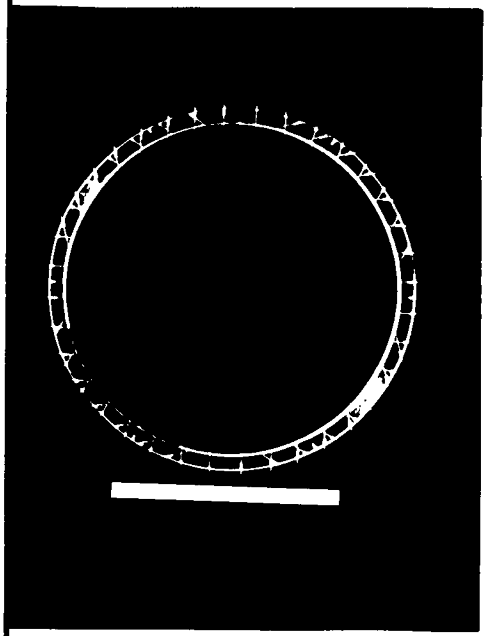


FIGURE 86

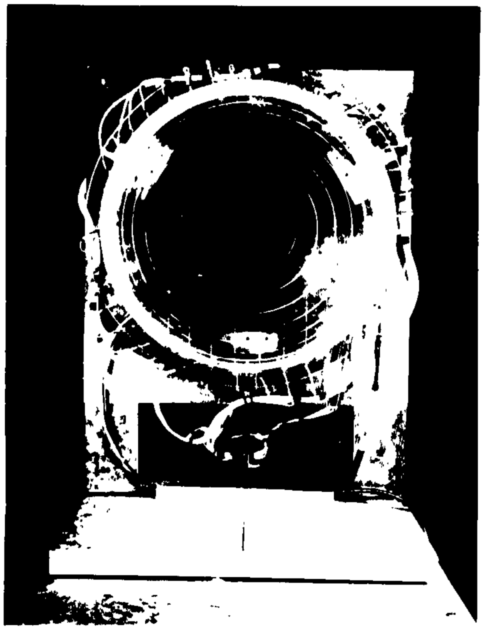


FIGURE 87

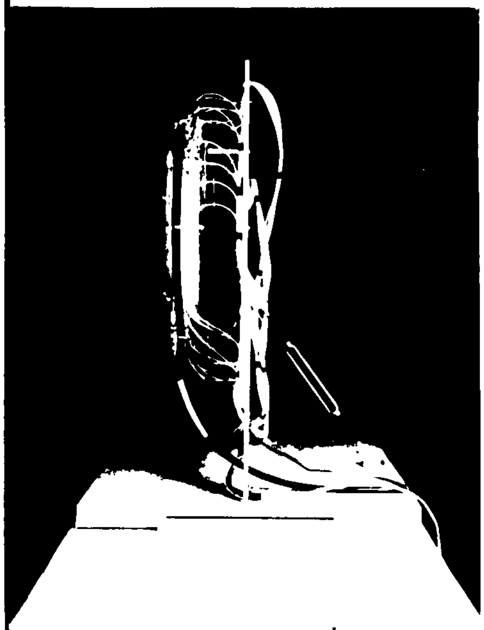


FIGURE 88

FIGURE 89

inconel alloy of sufficient thickness to provide a resistance of 500 to 1000 ohms/square. The concentric optical figuring rings were electrically isolated by removing the inconel coating and a small amount of glass with a high-speed hand grinder over zones 1/16 to 3/32 inch wide.

When this apparatus was tested the following difficulties were encountered:

(1) The optical figures showed large errors of various magnitudes over an outer zone which extended about two to six inches inside the membrane support ring in a random pattern. These errors were greatest adjacent to the edge of the support ring and gradually decreased with distance from the support ring and in some cases extended to the membrane center. These errors were of sufficient magnitude to produce astigmatic distortions of a "point" target image that extended from one to about ten milliradians in various directions in a random pattern. These errors were usually sufficiently large to be seen by eye when the mirror surface was viewed without the aid of the more critical Ronchi test.

(2) When the deflection electrode wires shown in Figure 86 were connected to successively increasing potentials using the type of network shown in Figure 73 a strong "Venetian blind" effect was observed due to the effect of the electric field of each electrode wire upon the membrane. The effect was noticeable even when the membrane mirror was viewed directly by eye without more critical optical test means. Potential differences in the order of 100 volts between wires caused such effects

while producing scarcely perceptible rotation of the mirror axis, even when spacer ring 9 and electrode ring 10 were interchanged from the positions shown in Figure 72.

j. Analysis Of Difficulties Experienced With The First Experimental Membrane Mirror Assembly

It was suspected that the large astigmatic distortions described above in Section 2.i. were caused by electrical field irregularities at the periphery due to non-uniform leakage over the inside surface of the membrane support ring. This was proven correct by utilizing pressure deflection.

Pressure test apparatus was devised by removing the crossed-wire grid-type deflection electrode and spacer ring from the assembly shown in Figures 72, 87 and 88. All holes were sealed with plastic electrical tape and the membrane support ring was sealed to the electrode plate by means of vacuum grease. Small pressure differentials were produced using the suction apparatus shown on Page 9 of Report No. 1. Although pressure deflection, for reasons given in Report No. 1, necessarily resulted in a flat-bottomed optical figure the resulting curved Ronchi fringe patterns observed were extremely symmetrical out to the very edge of the membrane.

There existed two possible means for eliminating the distortions caused by electrical leakage when using electrical means for producing the optical curvature. The first means required that the inner surface of the membrane support ring be made electrically conductive while the second means required that the membrane support ring be inverted so that the side to which the membrane was attached faced the curvature-producing electrode rather than the object viewed. This second means was checked experimentally using the apparatus shown in Figure 89 in which the membrane directly faced the curvature-producing electrode with a 2 inch air gap between the membrane and electrode. This inversion of the position of the membrane was found to eliminate the undesired peripheral distortion. The first means additionally would have required that the inside surface of the membrane support ring be divided into two or more electrically-isolated rings at adjustable potentials in order to provide adequate control over the optical figure at the outer periphery. This would have added complexity not involved with the second means.

While substitution of very large diameter wires or flat conductive strips for the thin wires previously used would provide greater axis deflections and while a greater number of such strips would reduce the Venetian blind effect to a negligible value it would be necessary also to provide a complex potential gradient pattern along each electrode bar or strip in order to maintain a parabolic optical figure, as discussed on Pages 112 and 113 of Report No. 1.

In view of the above problems it was concluded that the basic design was unsatisfactory and that an entirely new axis-deflection principle would have to be developed.

k. <u>A Review Of Membrane Mirror Functional Requirements And Possible Designs</u>

The membrane mirror and electrode system must satisfy the following basic requirements:

(1) The normally-flat membrane mirror must be deflected to the desired degree of concave curvature.

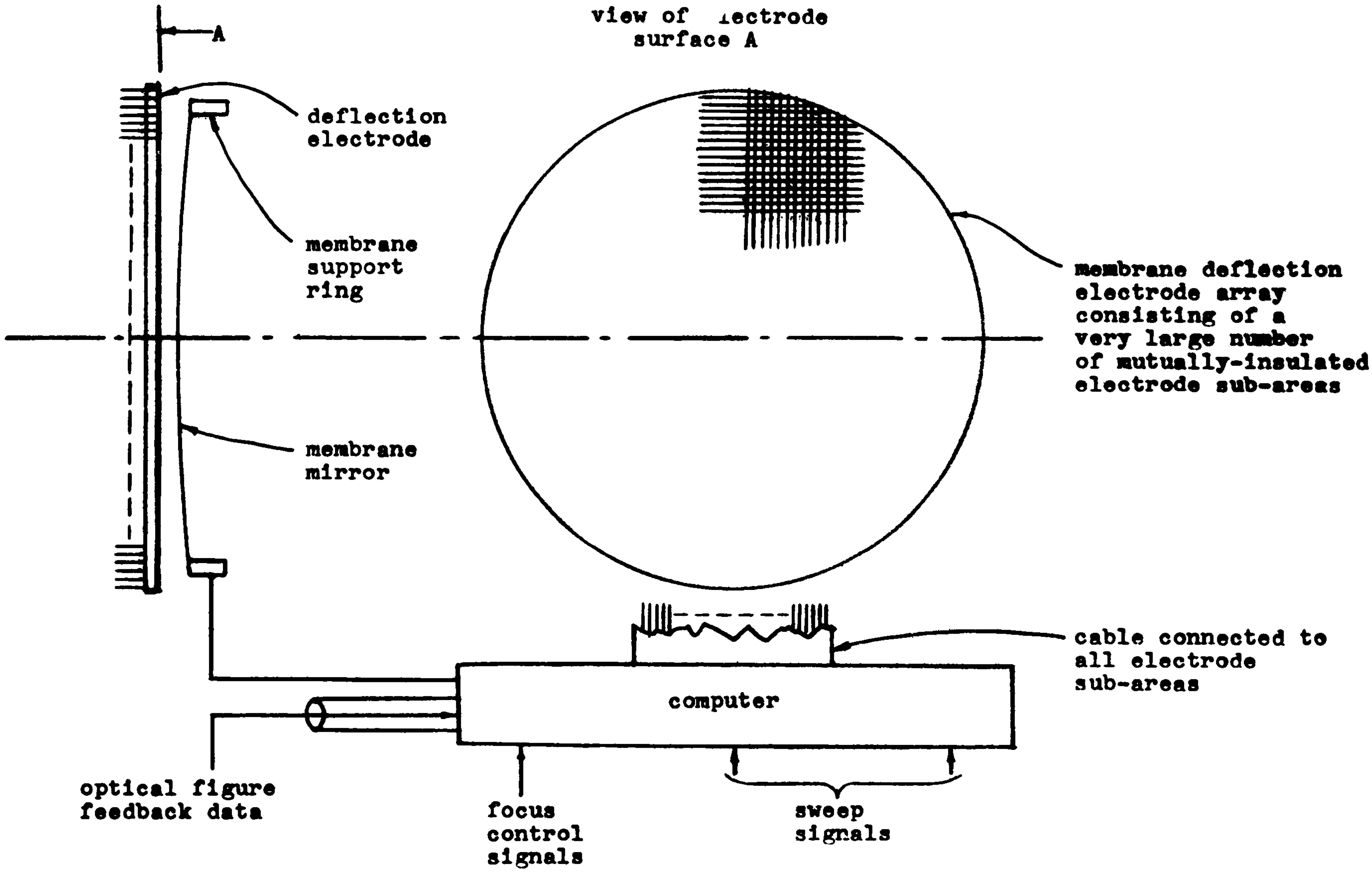
(2) Means must be provided for accurate adjustment of the concave optical curvature to an accurate parabolic figure. Preferably, this must be accomplished by adjustment of the potentials of several concentric zone rings on the main or curvature-producing deflection electrode. Previous experience has shown that when membranes are properly applied to the membrane support ring they are so uniform that optical figuring may be done on a zonal basis similar to that used in figuring rigid optical mirrors. Therefore, only concentric electrodes are necessary.

(3) Means must be provided for deviation of the optical axis through $\pm$ 0.5° while the parabolic figure is maintained with sufficient accuracy to permit one milliradian resolution to be obtained at F/3. This function must be accomplished with the least possible complexity of both the deflection electrode structure and the circuitry associated with them.

It was concluded (a) that since peripheral irregularities could be eliminated by placing the membrane support ring so that the side to which the membrane is attached faces the main or curvature-producing electrode and (b) that since the use of concentric zone rings having adjustable electric potentials had previously been proven practical (Report No. 1, Section 3.c.) these two design principles should be utilized. It remained, then, to devise a more efficient means for optical axis deviation having negligible "Venetian blind" or equivalent effect upon the optical figure. However, it was concluded that due to the complexity of the associated circuitry the use of deflection electrode wires or strips was not practical at this stage of the development.

Further consideration of generalized designs of unlimited complexity led to the realization that if the large flat electrode were divided into a very large number of unit areas practically any desired static or dynamic optical figure could be achieved provided electrical circuitry of computer complexity could be utilized as shown in Figure 90. However, even a far simpler system such as shown in Figure 91 would require circuitry too complex for this stage of the development.

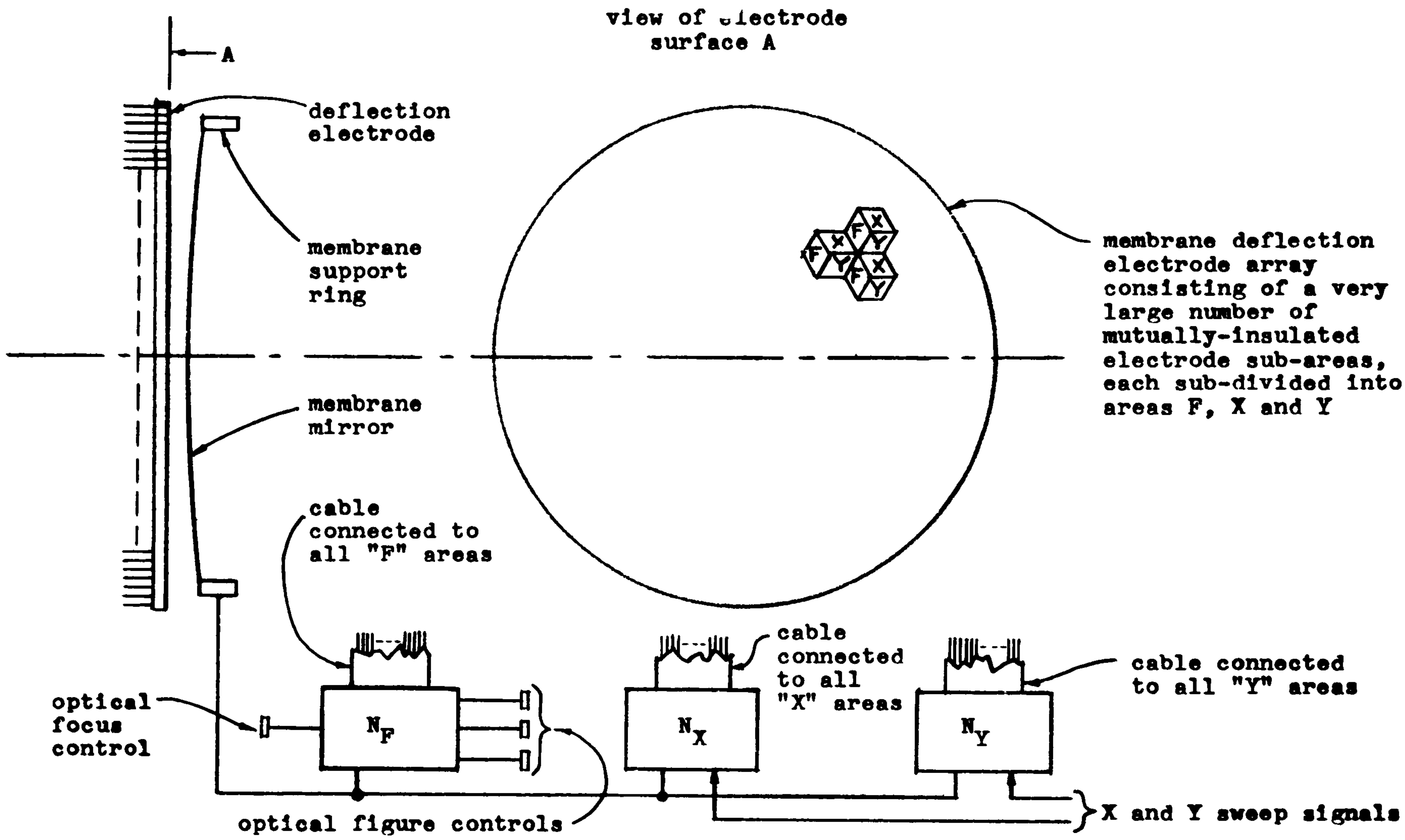
The above thinking led to the decision to utilize the least complex electrode structure and circuitry that could be devised. One such arrangement is shown schematically in Figure 92. This arrangement requires only one very simple voltage divider network for each deflection axis and one simple voltage divider network for electrical adjustment of the optical figure and focal length. Radial "wheel-spoke" distortions (the equivalent of the "Venetian blind" effect caused by the deflection electrode wires shown in Figure 72) can be reduced to a negligible magnitude by providing a sufficient number of peripheral segments on the deflection electrodes. The seeming loss of aperture caused by the ring type deflection electrodes is actually not peculiar to this simplified design since it is geometrically and physically impossible to utilize optically the entire mirror membrane area out to the periphery while axis deviation occurs. This clearly results (a) from the necessary attachment of the membrane mirror to the immovable edge of the membrane support ring and (b) from the finite elastic elongation range of all materials.



SCHEMATIC DIAGRAM OF A HIGHLY GENERALIZED
MEMBRANE MIRROR SYSTEM

FIGURE 90

IRCO CORPORATION, NEW YORK, N. Y.

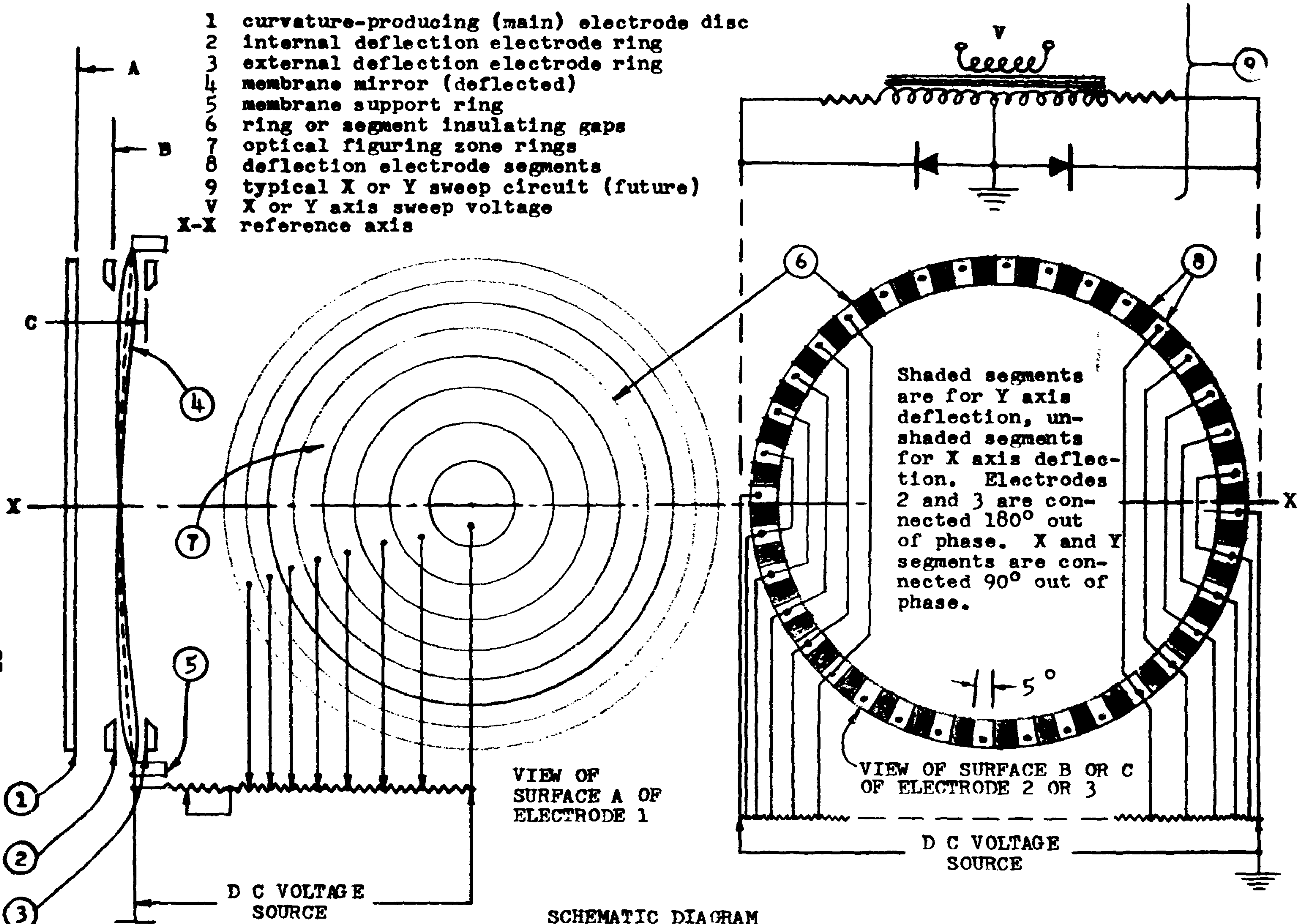


N_F, N_X and N_Y are sophisticated electrical networks

SCHEMATIC DIAGRAM OF A GENERALIZED MEMBRANE MIRROR SYSTEM

FIGURE 91

IRCO CORPORATION, NEW YORK, N. Y.



SCHEMATIC DIAGRAM

FIGURE 92

MEMBRANE MIRROR WITH ELECTRICALLY-ROTATABLE OPTICAL AXIS

IRCO CORPORATION, NEW YORK

1. Description Of The Final Experimental Membrane Mirror Assembly

Figure 93 shows the mechanical structure of the membrane mirror assembly used in the final experiments as shown schematically in Figure 102. The numbered parts shown in Figure 93 are as follows:

1 - plexiglas support parts

2 - aluminum base

3 - plate glass electrode (main or curvature-producing)

4 - soft rubber washers

5 - curvature-producing electrode tilt adjustment screws

6 - support bushing

7 - curvature-producing electrode support shaft (axial movement of this shaft permitted the position of the electrode to be varied)

8 - plexiglas insulating flange

9 - electrical connections to optical figuring zone rings

10 - pure teflon insulating ring (this ring covered the three outer optical figuring zones of electrode 3 which were not used)

11 - electrical connections to internal deflection-electrode segments

12 - electrical connection to membrane support ring and membrane

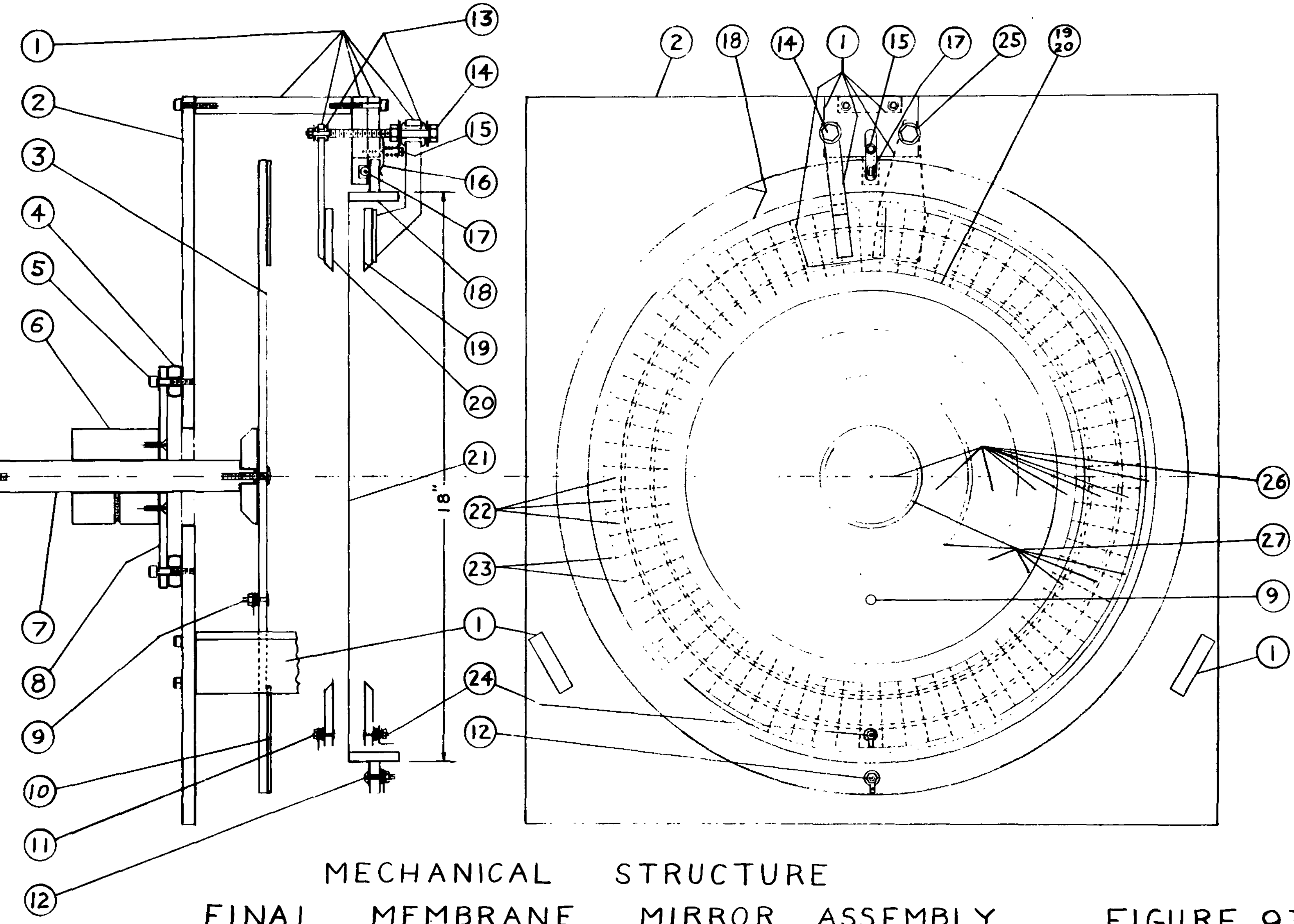
13 - rubber grommets

14 - external deflection electrode position adjustment screw

15 - membrane support ring clamp screw

16 - membrane support ring clamp

17 - ball bearing seats for membrane support ring



MECHANICAL STRUCTURE
FINAL MEMBRANE MIRROR ASSEMBLY

FIGURE 93

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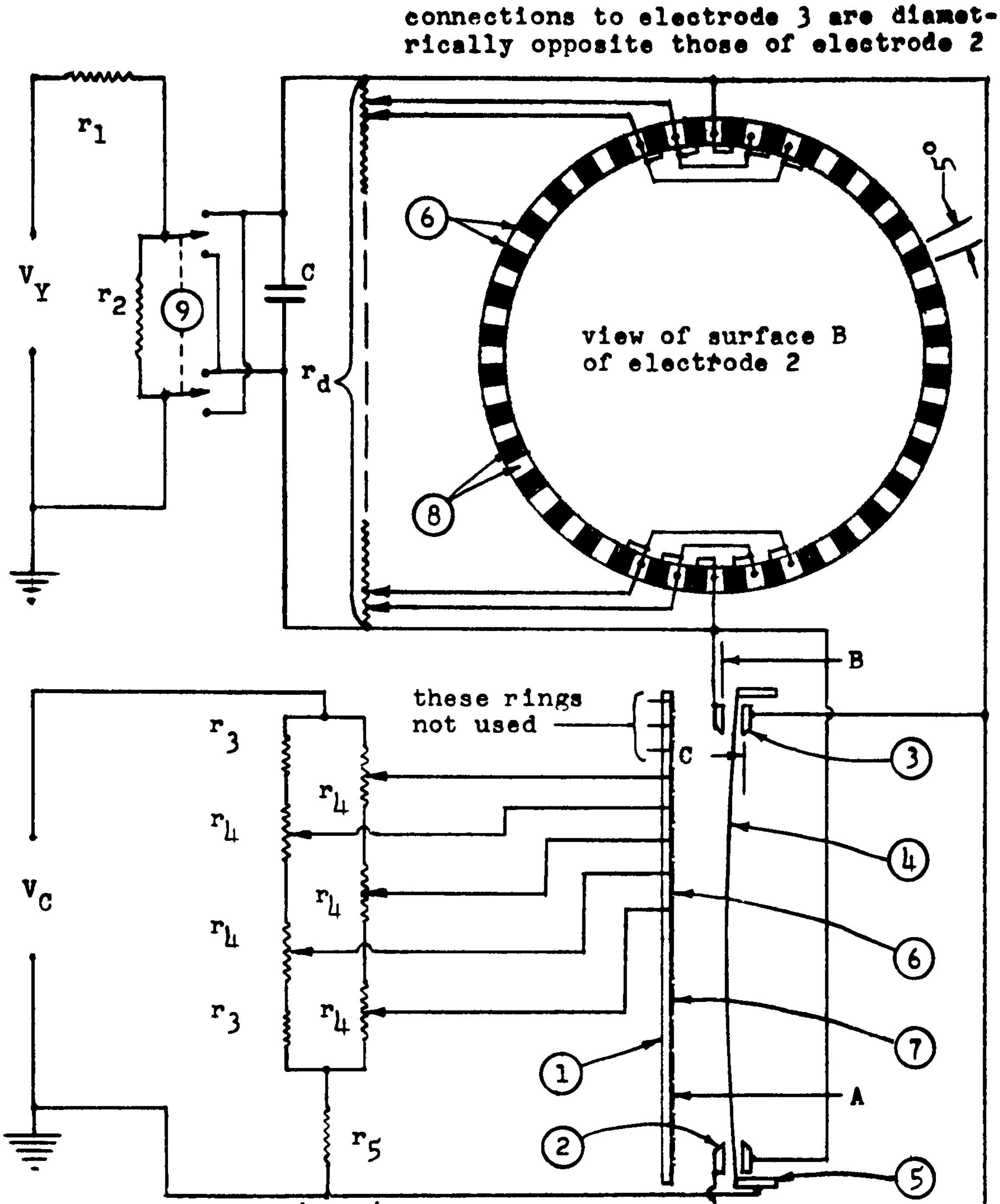

1 curvature-producing (main) electrode
2 internal deflection electrode ring
3 external deflection electrode ring
4 membrane mirror (axis not deflected)
5 membrane support ring
6 ring or segment insulating gaps
7 optical figuring zone rings
8 deflection electrode segments
9 deflection reversing switch
V_Y vertical plane deflection voltage (DC)
V_C curvature-producing voltage (DC)
C deflection delay capacitor (to round-off switching square wave fronts that would cause undesired transient membrane vibrations (.01 mfd)

r_1 = 7.5 megohms
r_2 = 15.0 "
r_3 = 2.7 "
r_4 = 5.0 "
r_5 = 33.0 "
r_d = 18.0 " total resistance

SCHEMATIC DIAGRAM - FINAL TEST CIRCUITS

FIGURE 102

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18 - pyrex membrane support ring

19 - external deflection electrode

20 - internal deflection electrode

21 - membrane mirror

22 - deflection electrode segments

23 - insulating gaps between deflection electrode segments

24 - electrical connections to external deflection electrode segments

25 - internal deflection electrode position adjustment screw

26 - optical figuring zone rings (Only the center dot and the four surrounding zones were used in the final assembly. The three outer zones were grounded.)

27 - insulating gaps between optical figuring zone rings

The plane of the curvature-producing electrode was tiltable over a small range at four equidistant points by means of screws 5. The membrane support ring and deflection electrodes were supported at three equidistant points as shown at the top of the drawing. In order to simplify the drawing these details have been omitted from the drawing at the 120° adjacent points. It will be seen that both deflection electrodes and the main or curvature-producing electrode were independently adjustable along the optical axis relative to the membrane support ring. The three electrodes and the membrane support ring were mutually insulated from each other by the plexiglas material used for support construction.

Figures 94, 95, 96, 97, 98, 99 and 100 show parts of the membrane mirror system shown in Figure 93 in various stages of assembly. All electrodes were constructed from

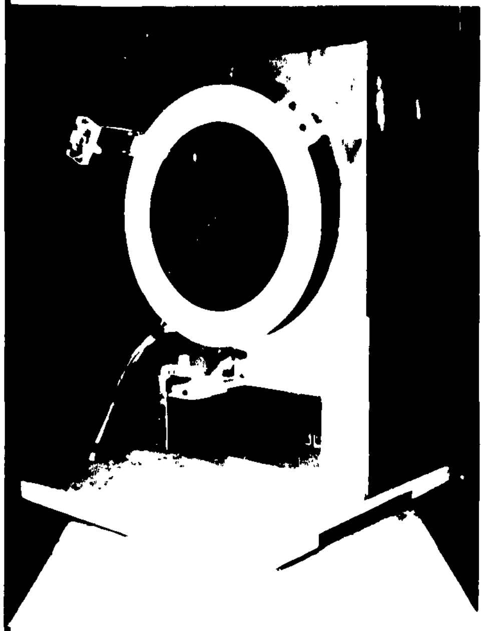

FIGURE 94

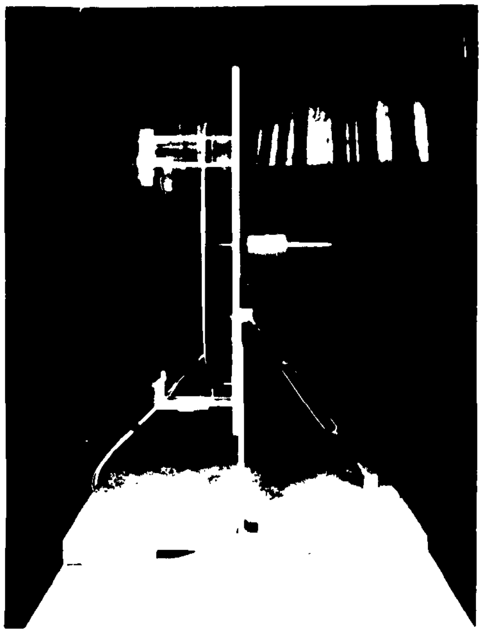

FIGURE 95

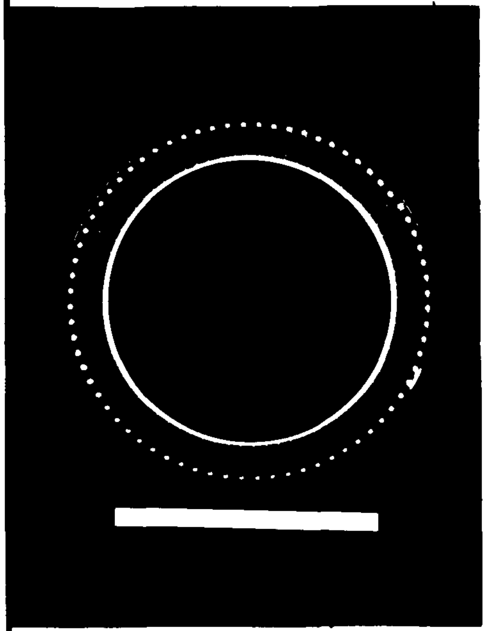

FIGURE 96

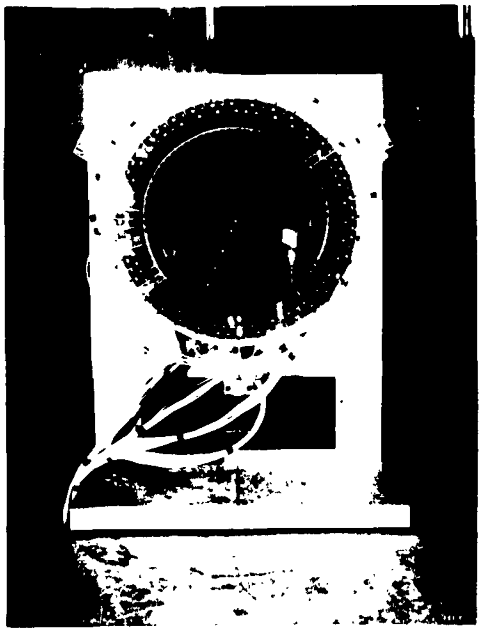

FIGURE 97

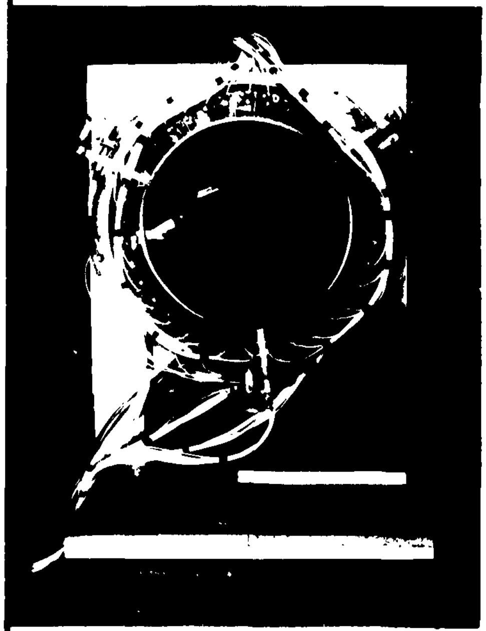

FIGURE 98

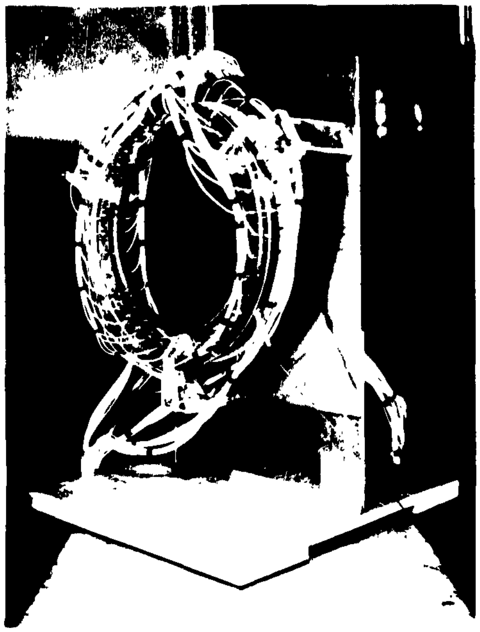

FIGURE 99

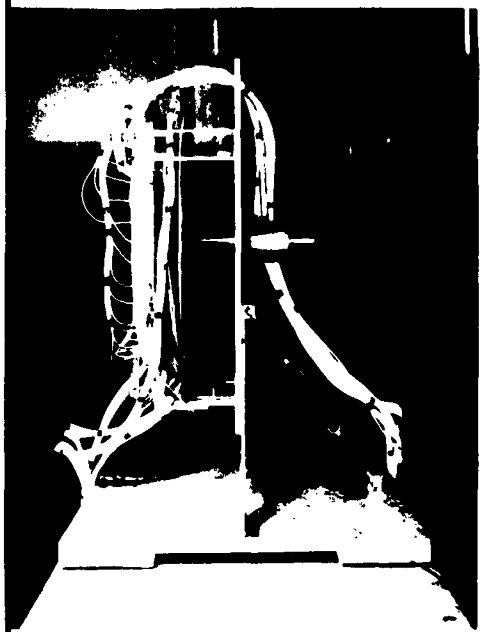

FIGURE 100

FIGURE 101

1/4 - 5/16 inch thick selected ultra-flat plate glass. The actual electrode surfaces consisted of evaporated inconel alloy of sufficient thickness to provide a resistance of 500 to 1000 ohms/square. Such a surface was sufficiently hard to permit frequent cleaning and handling without rubbing off. The concentric electrode zone rings used for optical figuring were produced by grinding off this material and part of the plate glass base using a high-speed hand grinder. The radial deflection electrode segments were produced by grinding in the same manner. The spacing between zone rings and electrode segments produced by grinding varied between 1/16 and 3/32 inch and provided adequate insulation for the experiments described in this report. Electrical connections to these rings and segments were made by standard round-head brass bolts which made direct contact with the inconel surface and passed through holes drilled in the glass. The bolt heads were machined flat to within about 0.025 inch from the inconel surface to minimize local field concentrations. A 13 inch ID x 18 inch OD x 1/16 inch pure teflon sheet was attached by "Pliobond" cement to the main electrode so that it covered the area under the inner deflection electrode. This area included the three outer concentric zone rings which were not used. This insulation was found necessary to prevent occasional voltage breakdown during experimentation when the spacing between the main electrode and the inner deflection electrode terminals was reduced. The inner circumference of each deflection electrode was beveled approximately 45° in order to eliminate irregular field effects and to minimize edge fields which would reduce the useful aperture below the limits imposed by the basic deflection electrode structure. Figure 101 shows a general view of the membrane mirror assembly, the electrical circuitry and the image-observation optical components.

m. Calibration Of The Potential Distribution Between Deflection Electrode Segments

The basic $(1 \pm \cos \theta)$ potential distribution derived below in Section 2.n. for each deflection electrode was obtained by means of the potentiometer calibration set-up shown in Figure 103 using a hand-calibrated precision voltmeter having ranges of 0-1000 volts and 0-10,000 volts and 0.2% accuracy and an RCA Senior Voltohmist to detect potentiometer circuit balance. With this set-up the precision regulated DC supply was set at 1000 volts after stabilizing for approximately one hour. The adjustable DC supply was then set to values of $V = 1000\ (1 - \cos \theta)$ for 18 values of θ from 10° to 180° in 10° steps using the precision DC voltmeter. For each value of θ the appropriate potentiometer was adjusted to produce a null reading on the vacuum tube voltmeter using the 0-15 volt DC range. The 1000 volt setting of the precision voltage supply was checked with the precision DC voltmeter several times and found to be correct. The potential distribution was checked to within meter readability with the terminals of the voltage divider reversed. This proved the symmetry of the $(1 \pm \cos \theta)$ settings, the precision voltmeter calibration accuracy, and the low DC leakage of the RCA Voltohmist to ground through the AC line. This instrument was placed on a sheet of plexiglas.

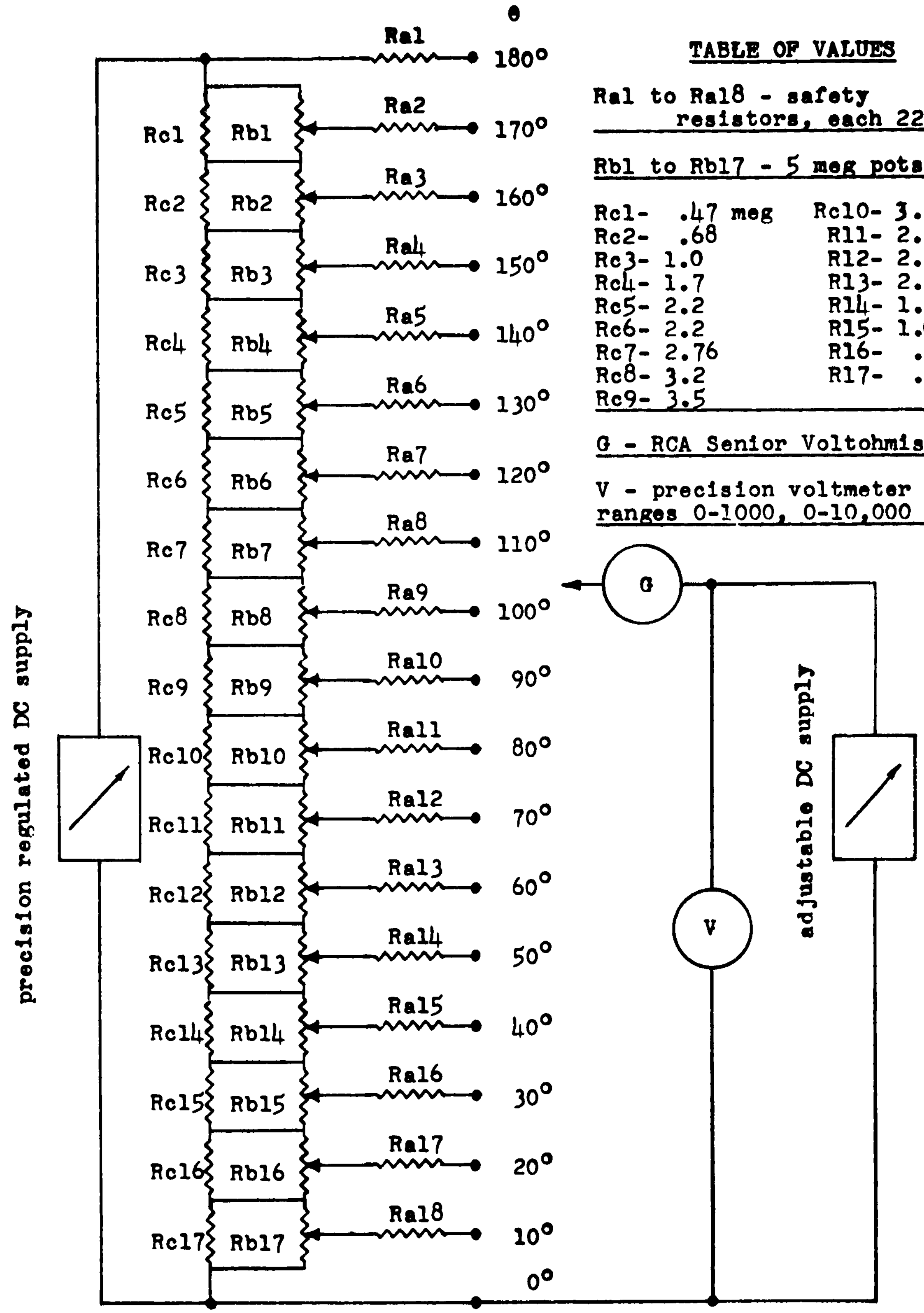

TABLE OF VALUES

Ra1 to Ra18 - safety resistors, each 22 meg

Rb1 to Rb17 - 5 meg pots

Rc1- .47 meg	Rc10- 3.2 meg
Rc2- .68	R11- 2.76
Rc3- 1.0	R12- 2.2
Rc4- 1.7	R13- 2.2
Rc5- 2.2	R14- 1.7
Rc6- 2.2	R15- 1.0
Rc7- 2.76	R16- .68
Rc8- 3.2	R17- .47
Rc9- 3.5	

G - RCA Senior Voltohmist

V - precision voltmeter - ranges 0-1000, 0-10,000

SCHEMATIC DIAGRAM OF DEFLECTION ELECTRODE SEGMENT POTENTIAL CALIBRATION CIRCUIT

n. **Voltage Distribution Between Deflection Electrode Segments**

It will be clear that a rigorous mathematical derivation of the potential distribution required between deflection electrode segments would be highly complex. Such a derivation would involve numerous parameters including at least the inside diameter of the deflection electrodes, the spacing of these electrodes from the membrane, the main electrode diameter and spacing, the free membrane diameter, the membrane physical constants and their radial distribution if not radially uniform. Since the time and cost of a rigorous derivation could not be justified in an experimental engineering development of this type a simple derivation of the approximate voltage distribution was made based upon the assumptions listed below. It was felt that such a first-order distribution could be modified subsequently by one or more correction factors if found necessary during the experimental work. The assumptions made were as follows:

(1) The membrane axis deflections are small.

(2) The membrane optical curvature is small.

(3) The effect of the electric charge on each electrode segment produces an adjacent membrane deflection proportional to the potential difference between the electrode segment and the membrane.

(4) The deflection electrodes are identical in all respects and their spacings on each side of the deflected membrane have been adjusted so that each electrode "pulls" the membrane an equal amount. The potential distributions on each electrode are the same but their zero points are diametrically opposite.

(5) Assuming any steadily-increasing potential difference between various points on the deflection electrode voltage divider in Figures 92, 102 and 103 the deflection produced by either deflection electrode operating alone causes the membrane to rotate about a region near the edge of the deflection electrode. When the second electrode operates in a similar manner so that the membrane is rotated about a region on the second electrode diametrically-opposite from the first the net effect is to produce rotation of the mirror about a region close to its original geometric center. The region over which the membrane is "pulled" by the electrical fields of the internal and external deflection electrode segments may be considered as a narrow concentric circular zone or band having an average diameter close to that of the inner edge of the deflection electrodes. Refer to Figure 104.

Let d = the displacement of the membrane adjacent to any electrode segment S_e on the external deflection electrode relative to point O_e

x = the distance of the "pull point" of segment S_e from the Y_e axis

V = the potential difference between the membrane and electrode segment S_e which contributes to displacement d when the action of all S_e and all S_i segments is integrated

k = the constant of proportionality between V and d

θ = the angular position of the "pull point" of electrode segment S_e from the X axis

R_p = average radius of the zone over which the deflection electrode "pull" is exerted

R_m = radius of the free area of the membrane mirror

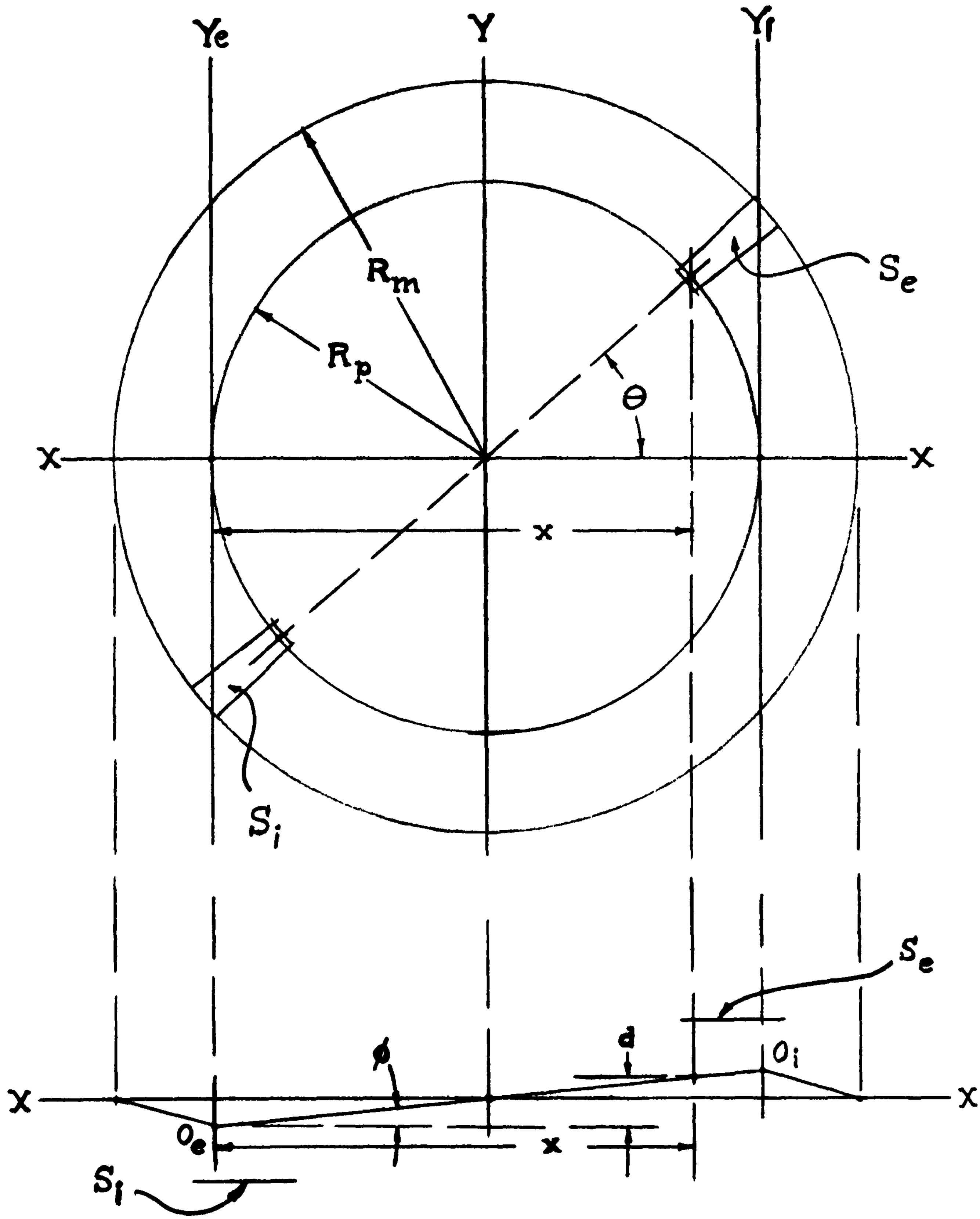

FIGURE 104

S_e represents any segment on the external deflection electrode

S_i represents a diametrically opposite segment on the internal deflection electrode

From Figure 104 and the above assumptions it will be clear that the combined action of the internal and external deflection electrodes will cause the membrane mirror to rotate through an angle ϕ about any of the three Y axes.

$$\text{Then } \tan \phi = \frac{d}{x} = \frac{k\,V}{x} \tag{1}$$

$$\text{and } x = R_p \quad (1 + \cos \theta)$$

$$\text{Therefore } V = \frac{R_p \tan \phi}{k} \quad (1 + \cos \theta) \tag{2}$$

For a diametrically opposite segment S_i on the internal deflection electrode we have the following relation with respect to point O_i and axis Y_i.

$$V = \frac{R_p \tan \phi}{k} \quad \left[1 + \cos\,(\theta \pm 180^\circ)\right] \tag{3}$$

this can also be written

$$V = \frac{R_p \tan \phi}{k} \quad (1 - \cos \theta) \tag{4}$$

From equations (2) and (4) it will be seen that the first order potential distribution about one deflection electrode must be of the form $1 + \cos \theta$ while about the other it must be of the form $1 - \cos \theta$. In each case this is the form of a peak-to-peak half sinusoid. Maximum deflection of the membrane due to the external deflection electrode will occur at $\theta = 0^\circ$ and zero deflection will occur at $\theta = 180^\circ$. Similarly, maximum deflection of the membrane due to the internal electrode will occur at $\theta = 180^\circ$ and zero deflection will occur at $\theta = 0^\circ$.

In view of assumption (1) it will be clear that for large angles of membrane deflection the peak-to-peak semi-sinusoidal potential distribution will have to be modified to a form having slightly flatter peaks than those of a sine wave in order to compensate for the increased electric field intensities at the extremes of deflection due to the decreased electrode-to-membrane spacings at those regions.

c. <u>Results Using The Final Experimental Membrane Mirror Assembly</u>

(1) <u>Membranes</u>

One, two, three, four and eight ply membranes having thicknesses of 15, 20, 30, 40 and 80 x 10^{-6} inch, respectively, were tried. The removal time after casting was varied from 3.0 to 10.0 minutes to obtain various tensions as discussed on Pages 59 to 65 of Report No. 1. Good membranes of all types were obtained when proper care was exercised and when the application apparatus was carefully adjusted. Before the addition of glyptal lacquer to the casting solution formula the membranes appeared to "creep" for several minutes before reaching a stable "set" for deflections of F/3. A similar return to the original state usually took place several minutes after the deflection voltages were removed. The addition of the glyptal lacquer appeared to reduce this creep to a very low value. A more careful study of this characteristic as related to membrane casting solution formulas should be included in any future work in connection with curved membrane mirrors.

Based upon previous experience it had been assumed that multiple-ply membranes were necessary to compensate various assymmetrical effects believed to be inherent in single-ply double membranes. At the time this report was prepared it was discovered that the optical uniformity of single-ply membranes appeared equal to that of the best multiple-ply membranes. A tentative explanation based upon limited "last minute" experience is that the non-uniformities encountered in the previous work were probably due to less careful alignment of the membrane and the membrane support ring at the instant of contact. At the time this report was prepared the most uniform membranes appeared to be single-ply double membranes of about 15×10^{-6} inch thickness removed about 10.0 minutes after casting. The membrane coating was gold evaporated as described above in Section 2.g. The coating appeared light green by transmitted white light.

(2) <u>Optical figuring before axis deflection</u>

The complete assembly shown in Figure 93 was provided with an 11 inch diameter concentric aperture stop located in front of the external electrode to mask the approximately 1 inch wide zone of edge distortion caused by the 13 inch ID deflection electrodes. The average potential (usually 16 to 25 KV) and spacing (usually 1.2 to 1.6 inches) of the main electrode relative to the membrane was varied to obtain a focal distance of 36 inches for targets located at 432 inches. This corresponds closely to F/3 and a focal length of 33 inches for targets at infinity.

With all segments of both deflection electrodes connected to the grounded membrane the potentials of the central dot and the four inner zone rings of the main or curvature-producing electrode were adjusted relative to the average potential using potentiometers r_4 in the test circuit shown in Figure 102 until a uniform Ronchi shadow pattern was obtained on the ground glass screen shown in Figures 61-A, 80 and 81 using the illuminated source grid (0.25 inch interval) shown in Figure 79. As the object-to-image distance was in the ratio of 12:1 the ratio of source grid spacing to interception grid spacing was also 12:1. It was usually possible to obtain an optical figure sufficiently close to parabolic* with maximum potential deviations from average of not over 500 volts between adjacent figuring zones. A source grid rather than a pinhole was normally used to obtain maximum light for test purposes. However, in some cases only a pinhole was used in lieu of the source grid and equivalent but much darker Ronchi fringes were obtained.

By adjustment of the main electrode slightly out of parallel with the plane of the membrane support ring overall membrane distortions of small magnitude could be compensated if carefully-made membranes were used. When the above described adjustments were completed the image of a 0.2 milliradian "point" source could be imaged with an estimated 90% of its energy within a one milliradian circle, as measured on the ground glass screen and grid shown in Figures 61-B, 82 and 83.

*Actually an ellipse very close to a parabola since the source grid was at a finite distance.

(3) <u>Adjustment of electrode spacings and electrode potentials</u>

The external and internal deflection electrode spacings were carefully adjusted by means of screws 14 and 25 shown in Figure 93 until the gaps between each electrode and the membrane with its axis deflected 0.5° were approximately equal at the diametrically opposite points where the membrane deflection was a maximum. DC potentials of alternate polarity were then applied to the potential divider and the two deflection electrodes using the switching circuit shown in Figure 102. Using a DC potential (usually 2000 to 5000 volts) sufficient to produce 0.5° deflections on each side of the reference axis the image of the 0.2 milliradian "point" source was observed on the ground-glass screens shown in Figures 61-B, 82 and 83. After adjustment of each electrode closely parallel with the membrane and after adjustment of the external electrode-to-membrane spacing slightly relative to the internal electrode-to-membrane spacing it was found that the target image could be moved $\pm 0.5^{\circ}$ from the main axis while an estimated 70 to 75% of its energy fell within a one milliradian circle. A very small adjustment of the main electrode potential was frequently required to obtain the smallest point target image when the image was deviated $\pm 0.5^{\circ}$ from its reference position. Typical spacings of the internal and external deflection electrodes relative to the uncurved and undeflected membrane were 0.4 inch and 0.2 inch respectively.

p. <u>Discussion Of The Final Test Results</u>

(1) <u>Accuracy of membrane type objective mirrors before axis deflection</u>

The accuracy of undeflected 11 inch aperture F/3 mirrors, while very close to one milliradian, could be greatly improved if (a) the membrane application apparatus (Figure 71) were improved, (b) air pressure pulses and drafts could be eliminated and (c) the casting solution formula could be further investigated and improved to eliminate the residual "creep" effects discussed above in Section 2.o.(1).

(2) <u>Aberrations of off-axis targets</u>

As expected, based upon past experience, it was observed that with the optical axis either deflected or undeflected the one milliradian order of resolution was not degraded to any significant degree when targets were situated 2° off-axis. This would, of course, be observed for all F/3 mirrors having one milliradian resolution, whether of the rigid or of the membrane type.

(3) <u>Optical figuring by means of concentric zone rings</u>

It was observed that membrane mirrors could be figured sufficiently close to spherical or parabolic to provide one milliradian resolution by adjustment of the potential differences between the four concentric zone rings and center disc on the curvature-producing electrode. When membrane uniformity was extremely good adjustments could be made to yield better than one milliradian resolution. No zonal errors were observed due to the limited number of optical figuring zones chosen.

(4) Deflection electrode segments

The 10° angular discontinuity between deflection electrode ring segments appears to be sufficiently fine to prevent troublesome "wheel spoke" distortions of the optical figure of membrane mirrors.

While deflections were produced about only one axis and 10° deflection electrode segments were obtained by jumping adjacent 5° segments the same target resolution should be obtained when alternate 5° segments are used for one deflection axis and the remaining alternate segments are used for a second deflection axis, as shown in Figure 92. However, with only 5° segments per axis it is to be expected that the deflection voltages will have to be doubled to obtain $\pm 0.5^{\circ}$ axis deviations. Such higher voltages may involve minor insulation problems when tests are made in laboratory atmospheres. Insufficient time was available to check these assumptions experimentally.

(5) Image resolution and amplitude of image deviation

Using the present geometrical and electrical parameters one milliradian resolution for $\pm 0.5^{\circ}$ axis deviations at F/3 appears close to the limits which can be achieved. However, from the experience now gained greater axis deflection angles and/or better target image resolution can be obtained with relatively simple variations of the basic design that was used. Since the modified parts needed would have required two to three additional months to construct, process and assemble it was not possible to achieve such improvements experimentally.

(6) Potential distribution between deflection electrode segments

The $\pm 0.5^{\circ}$ optical axis deflections were obtained using a peak-to-peak semi-sinusoidal potential distribution on the deflection electrodes and no attempt was made to modify this distribution as discussed above in Section 2.n. Larger deflection angles and/or better target image resolution might have been obtained if the $1 \pm \cos \theta$ potential distribution had been modified. However, it is believed that in future work it would be desirable to retain the simple $1 \pm \cos \theta$ distribution and to achieve higher deflection angles and resolution by variation of the geometrical parameters of the deflection electrodes and the physical parameters of the membrane.

3. RECOMMENDED WORK LEADING TO A PROTOTYPE SCANNER

a. Work Leading To A Useful Prototype Scanning System Design

(1) The apparatus shown in Figure 93 should be modified to permit motion of a point target over a 1° diameter circular path to be demonstrated at F/3 with one milliradian resolution.

(2) When a 1° diameter circular scan motion has been achieved the maximum frequency limits should be determined:

(a) in laboratory air

(b) in a vacuum

(3) Modify the membrane mirror assembly to provide increased optical axis deflection and/or improved target image resolution.

(4) Design a prototype membrane mirror scanning system.

b. Improvement Of Membrane Mirrors

(1) Modify the membrane application apparatus shown in Figure 71 to (a) improve the accuracy of alignment between the membrane and its support ring, (b) eliminate all relative motion between the membrane and its support ring and (c) exclude air vibrations, drafts and building vibrations at the instant they are brought into contact.

(2) Develop modifications of the present collodion-glyptal type membrane casting formula and also investigate other type membrane casting materials with a view toward (a) reduction of plastic flow characteristics to negligible values and (b) improvement of elastic limits.

(3) Develop specific membrane coatings required for space applications including coatings on both sides of the membrane to provide protection for the organic membrane material.

(4) Obtain elongation and Young's modulus data for the improved membrane material, before and after being coated with metal.

(5) Determine the effect of the environmental conditions in space upon the membranes which result from the development indicated in (2), (3) and (4) above.

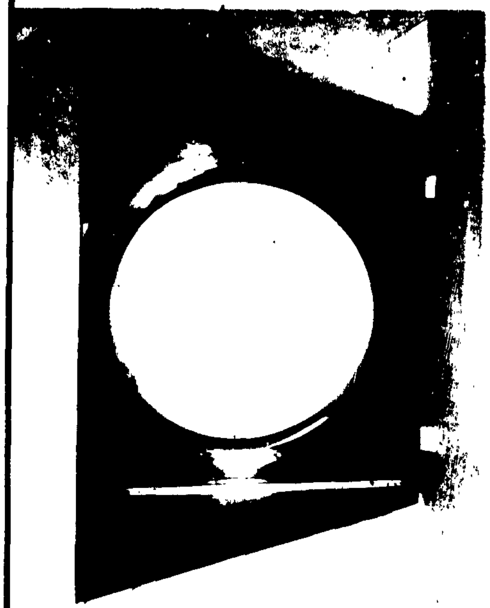

FIGURE 67

FIGURE 70

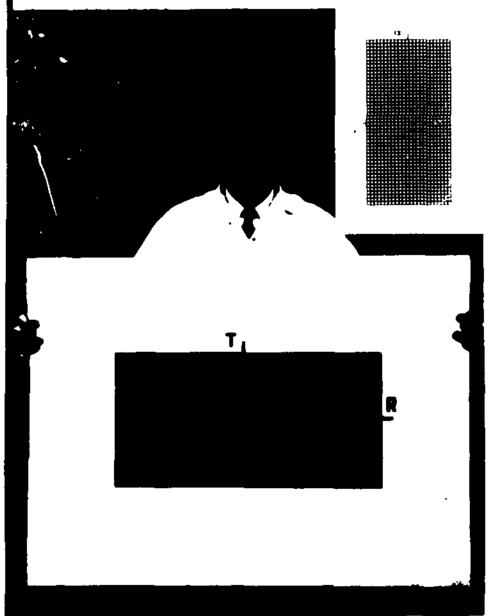

FIGURE 59

FIGURE 69

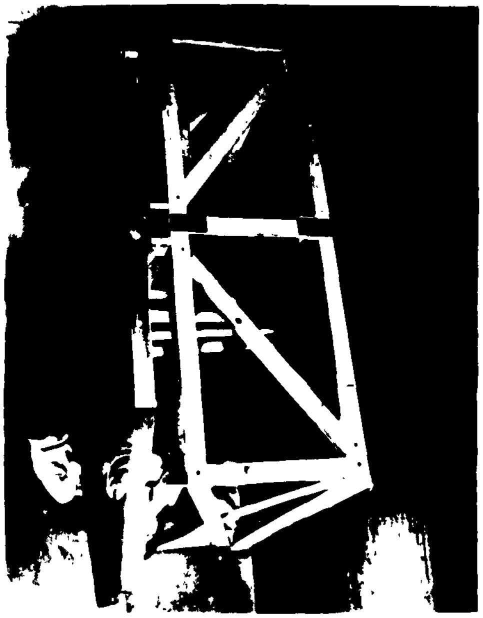

FIGURE 68

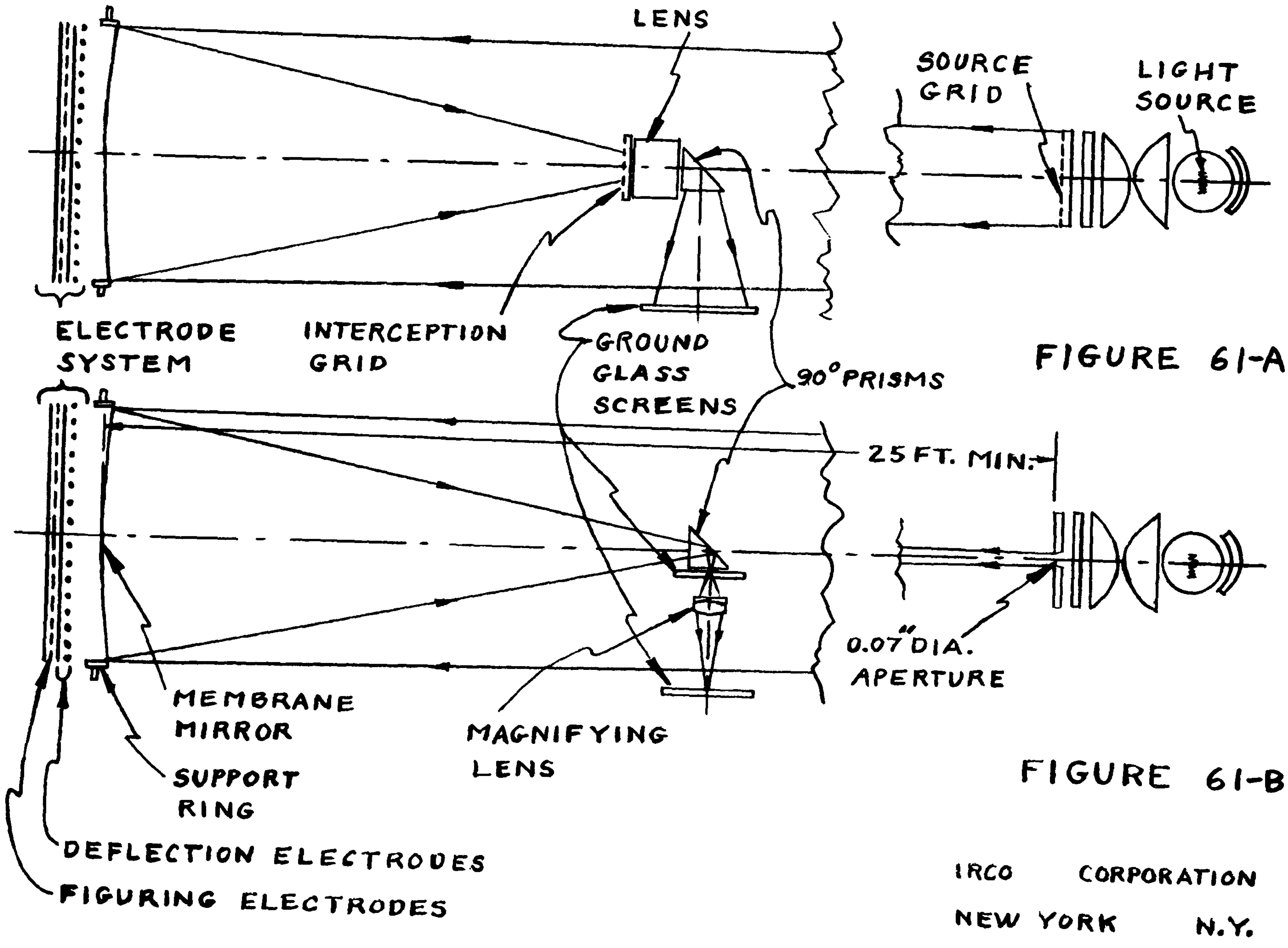

FIGURE 61-A

FIGURE 61-B

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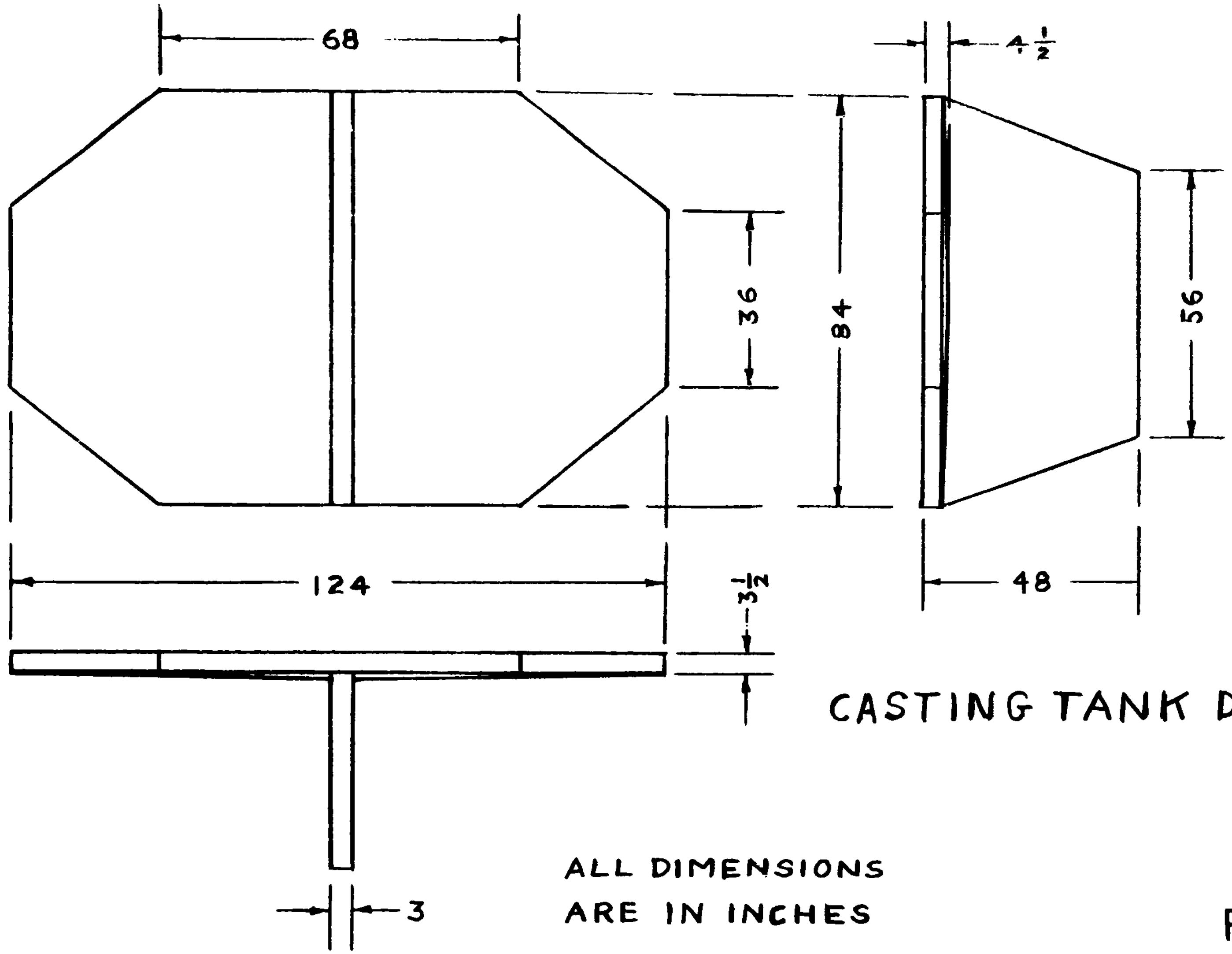

CASTING TANK DIMENSIONS

ALL DIMENSIONS
ARE IN INCHES

FIGURE 69

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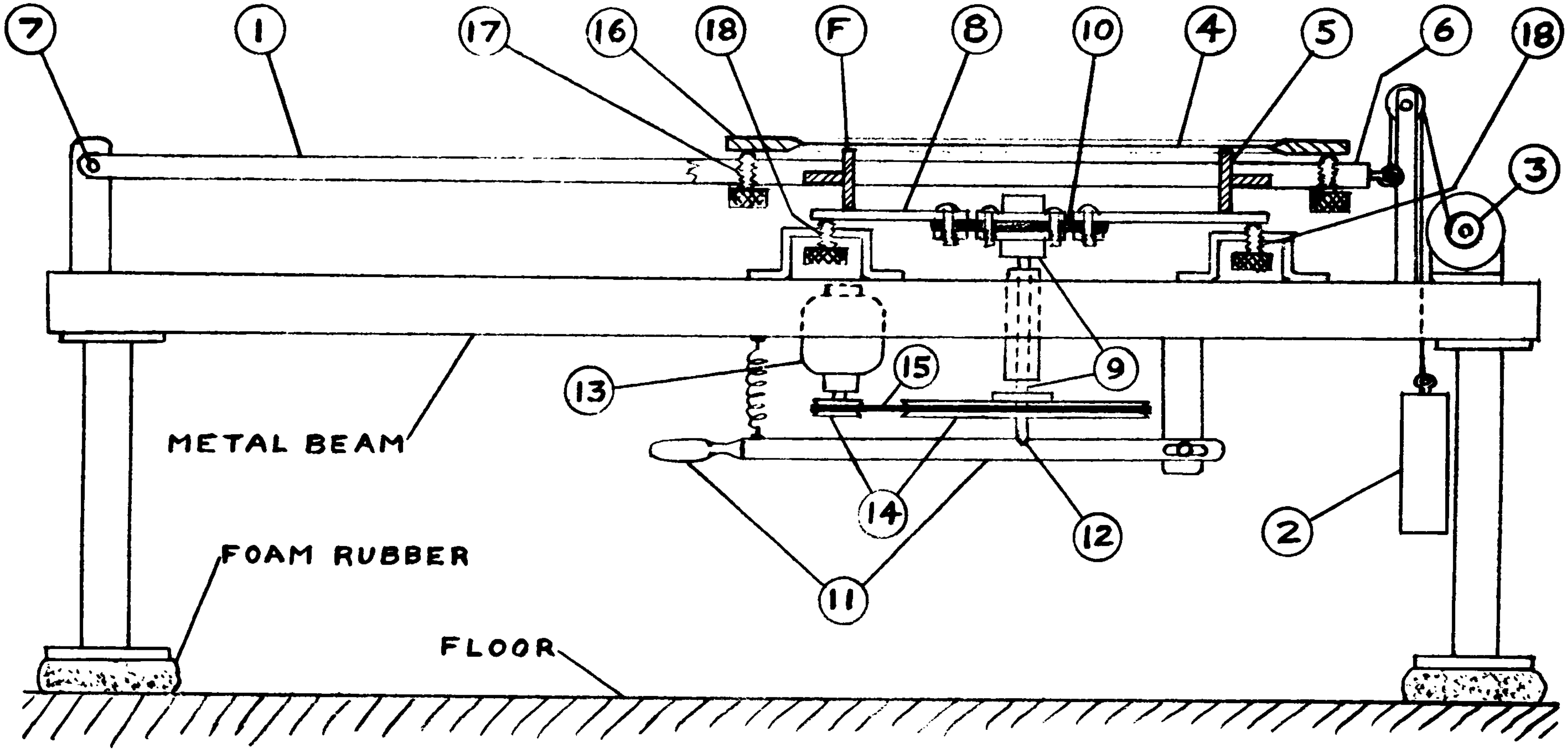

MEMBRANE APPLICATION APPARATUS

FIGURE 71

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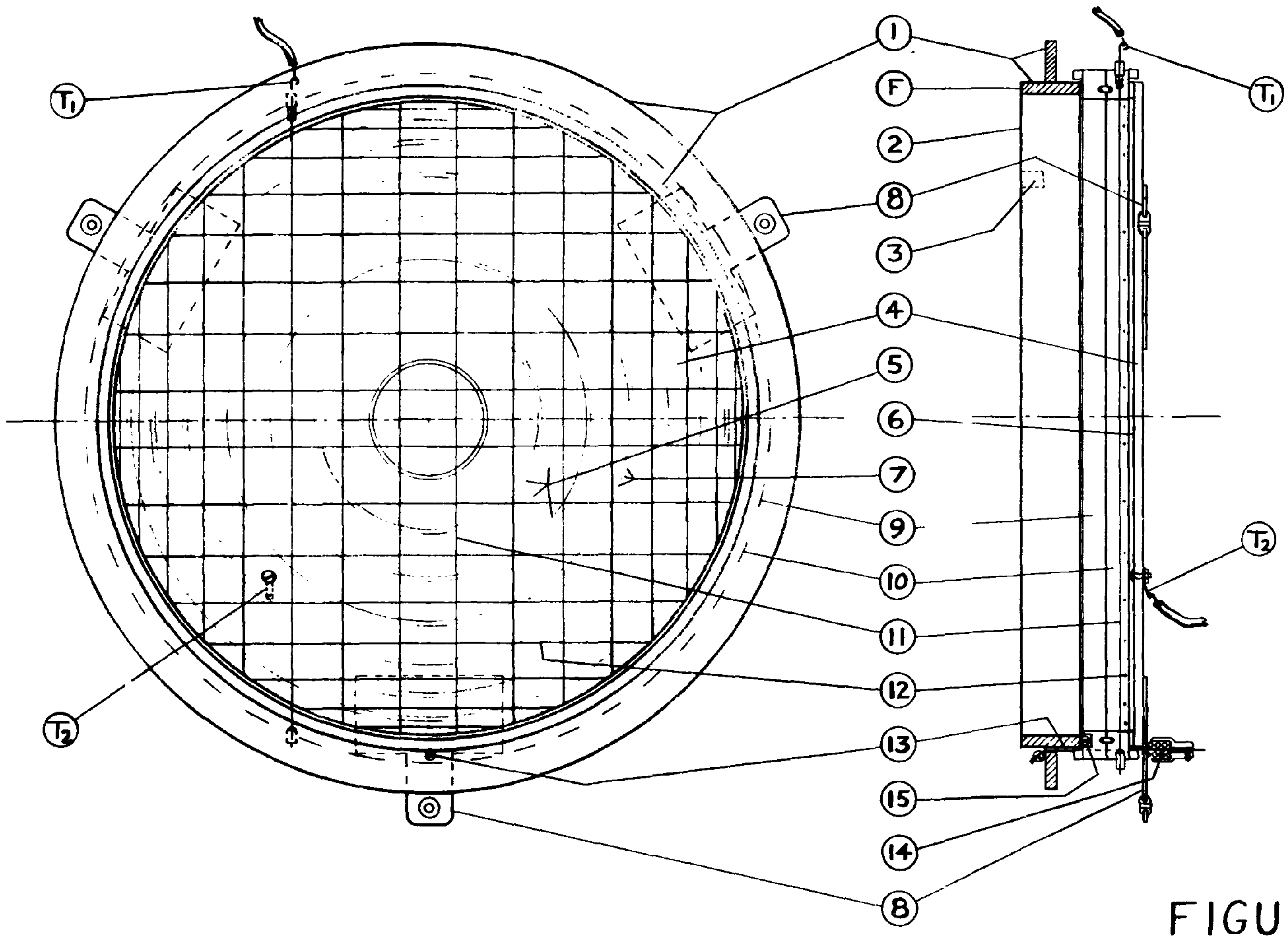

MEMBRANE MIRROR ASSEMBLY

FIGURE 72

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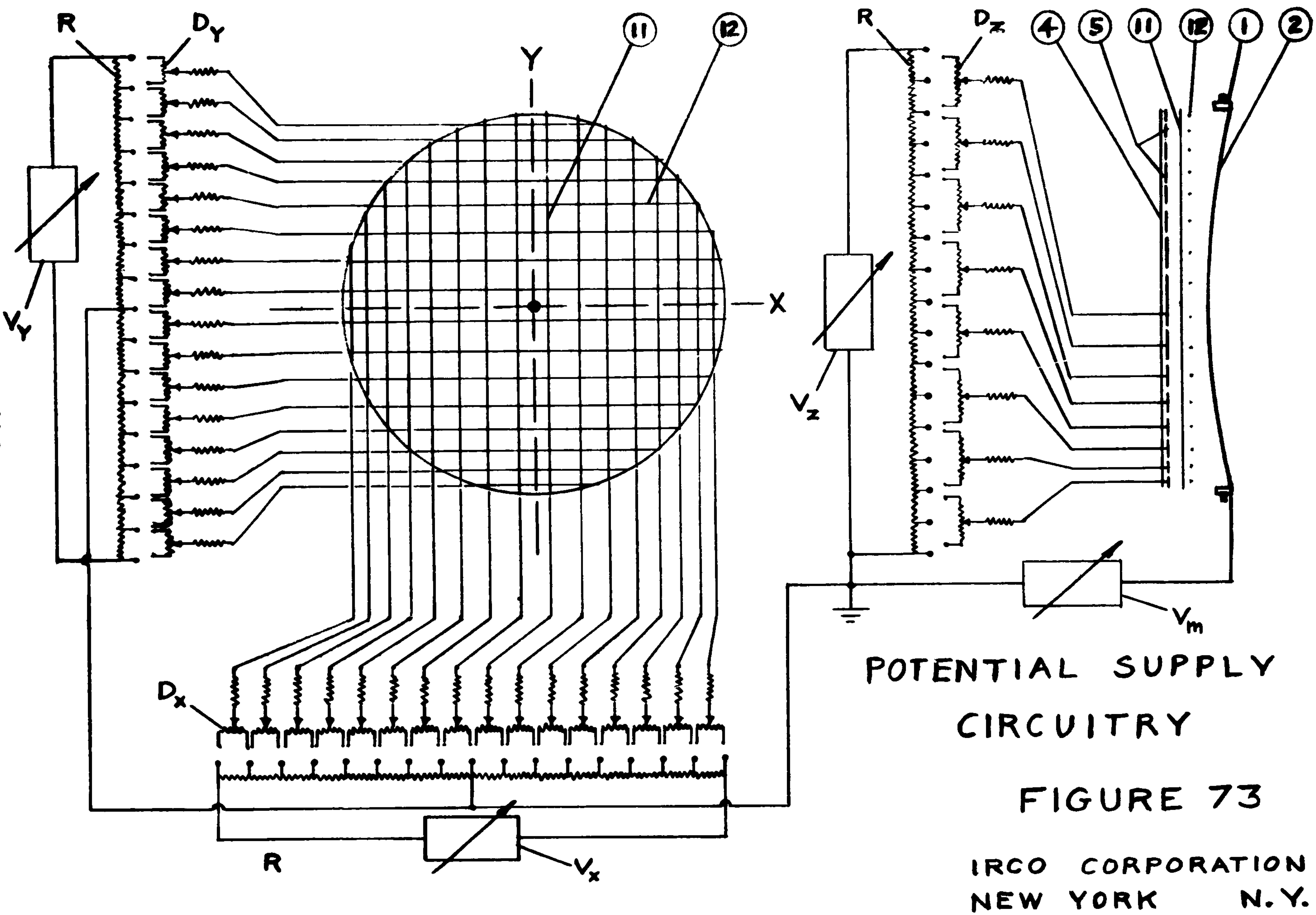

POTENTIAL SUPPLY
CIRCUITRY

FIGURE 73

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